EIC Nucleon Spin Science Program, including First Stage Goals

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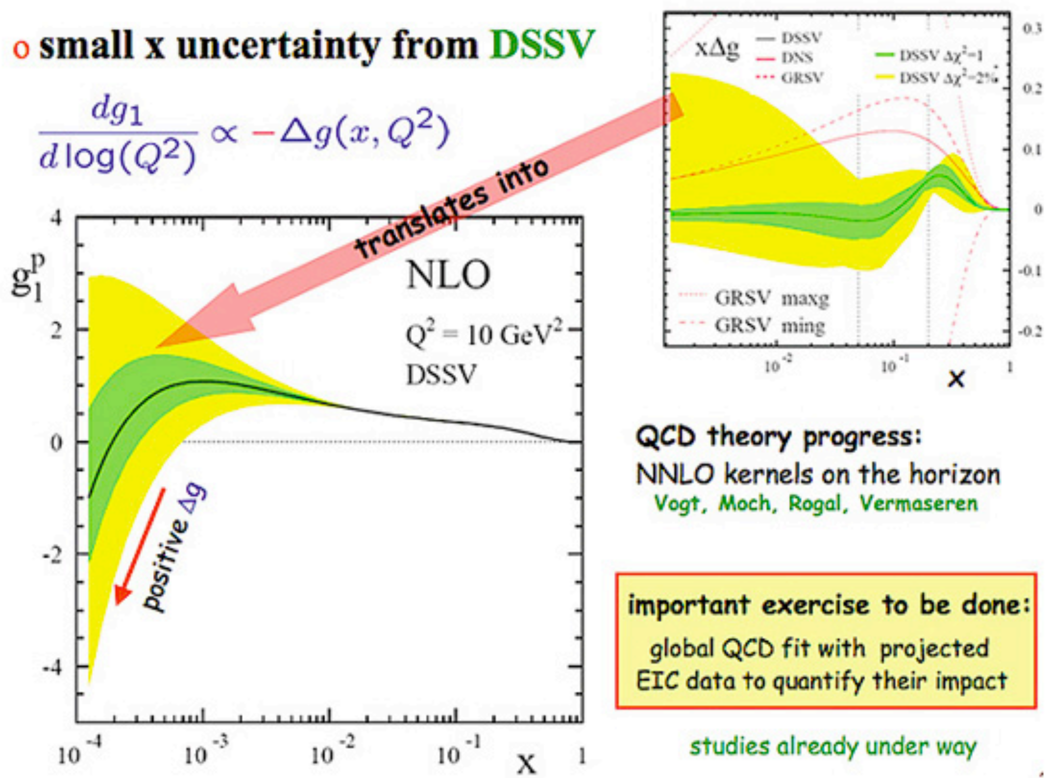
2011 RHIC & AGS Annual Users' Meeting
Workshop on Future Strategy for the Facility
BNL, June 22, 2011

Program @ Institute for Nuclear Theory

Gluons and the quark sea at high energies: distributions, polarization, tomography

September 13 to November 19, 2010



... The community must now work out the physics case for such a facility, showing on one side that its projected parameters and performance will be adequate for its physics goals, and on the other side that we have the theoretical tools to analyze the envisaged measurements. It is also important to situate the proposal with respect to other planned or proposed facilities ...

http://www.int.washington.edu/PROGRAMS/10-3/

Program @ Institute for Nuclear Theory

Gluons and the quark sea at high energies: distributions, polarization, tomography

September 13 to November 19, 2010

Organizers: D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang

Convenors: D. Hasch, M. Stratmann, F. Yuan (spin and PDFs),
M. Burkardt, V. Guzey, F. Sabatie (imaging),
A. Accardi, M. Lamont, C. Marquet (eA),
K. Kumar, Y. Li, W. Marciano (beyond SM)

Main Goal: Sharpen the science case for an EIC in preparation of NSAC LRP

Identify outstanding open questions in hadronic physics still relevant in 10+ years,
Devise key measurements in eN and eA to address these questions,
Identify experiment needs, requirements, feasibility, and quantify measurement capability.

Detailed write-up in progress,

Many Thanks, also to all fellow-participants - I will focus on (strongly) selected topics, and borrow heavily from your slides.

http://www.int.washington.edu/PROGRAMS/10-3/

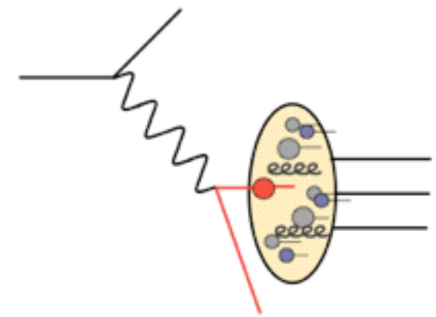
Kinematics

Definitions: $e = (0, 0, -E_e, E_e)$

$$e' = (E'_e \sin\theta'_e, 0, E'_e \cos\theta'_e, E_e)$$

$$p = (0, 0, E_p, E_p)$$

DIS



Invariants: $s = (e+p)^2$

$$q = e - e' \quad Q^2 = -(e-e')^2$$

$$x = \frac{Q^2}{ys}$$

no substitute for c.m. energy

$$y = (q.p)/(e.p)$$

Resolutions:

$$\left(\frac{\delta Q^2_e}{Q^2_e}\right) = \frac{\delta E'_e}{E'_e} \otimes \tan\left(\frac{\theta'_e}{2}\right)\delta\theta'_e$$

photoproduction

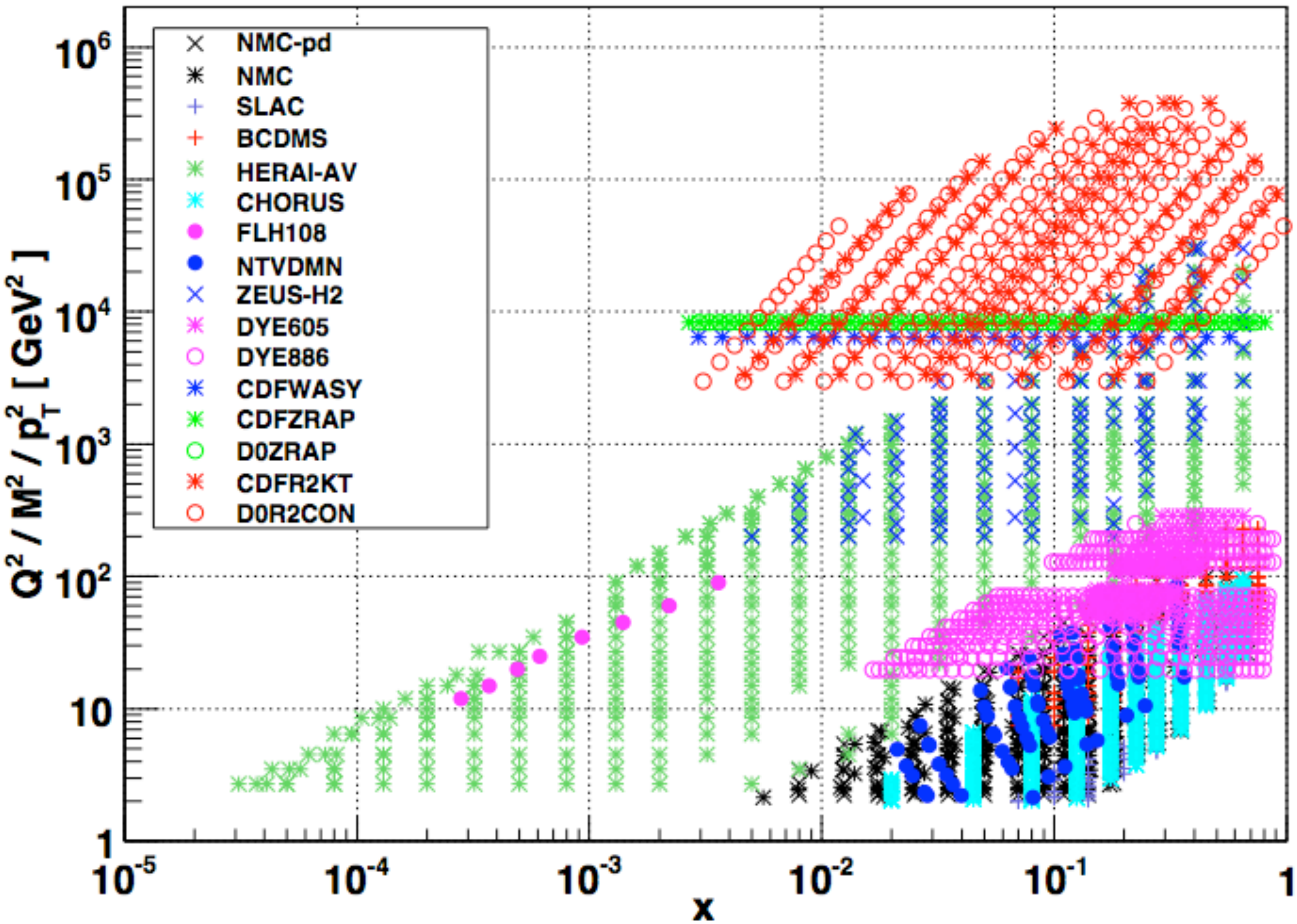
$$\left(\frac{\delta x_e}{x_e}\right) = \left(\frac{1}{y_e}\right)\frac{\delta E'_e}{E'_e} \otimes \left[\frac{x_e}{E_e/E_p} - 1\right]\tan\left(\frac{\theta'_e}{2}\right)\delta\theta'_e$$

low y

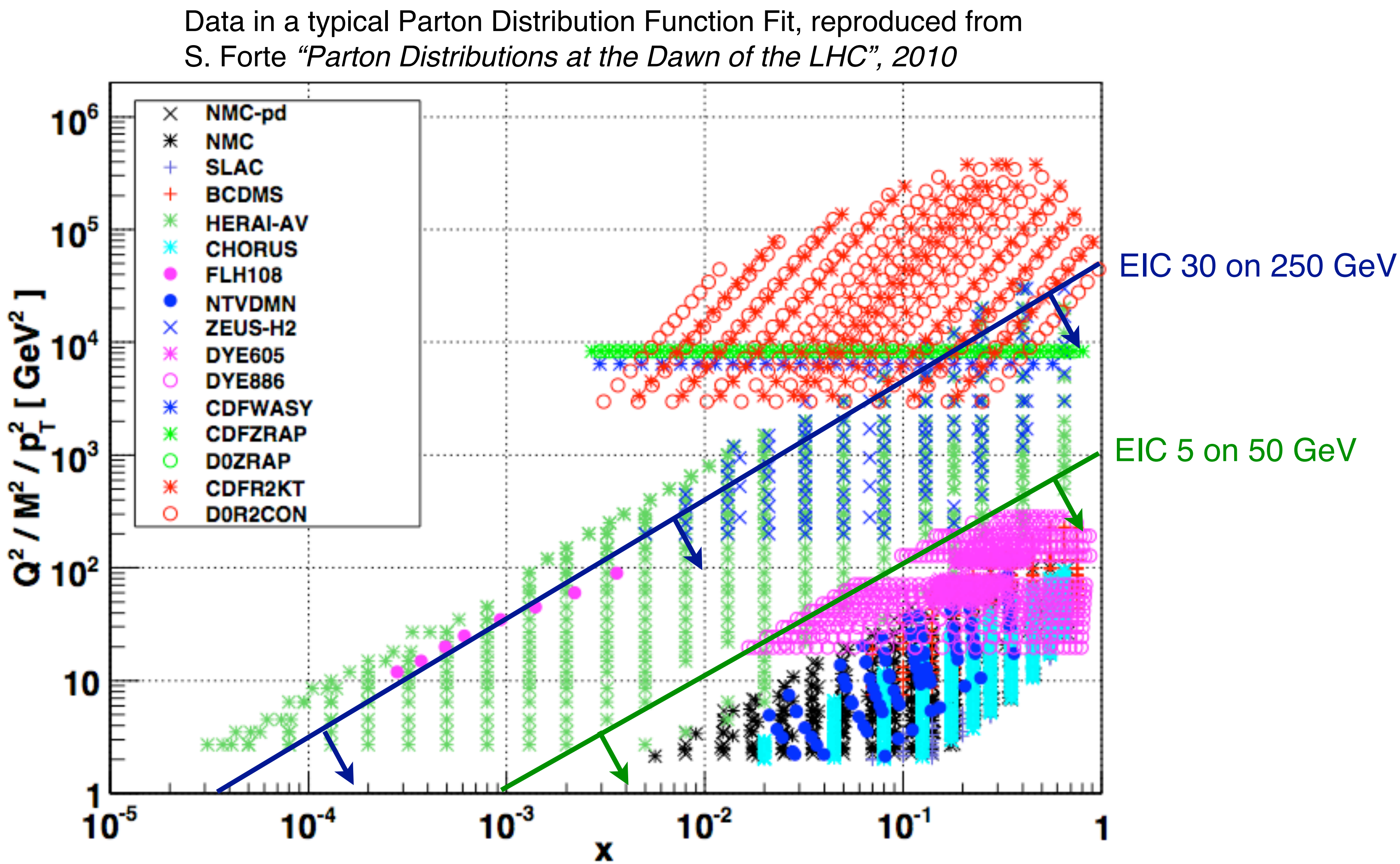
Note: kinematics can in principle also be reconstructed also from the current jet; to be demonstrated in nuclear environments.

Kinematics and Coverage

Data in a typical Parton Distribution Function Fit, reproduced from
S. Forte *"Parton Distributions at the Dawn of the LHC"*



Kinematics and Coverage



HERA already covered this with unpolarized proton beams;
What is new and/or can be done (much) better at EIC?

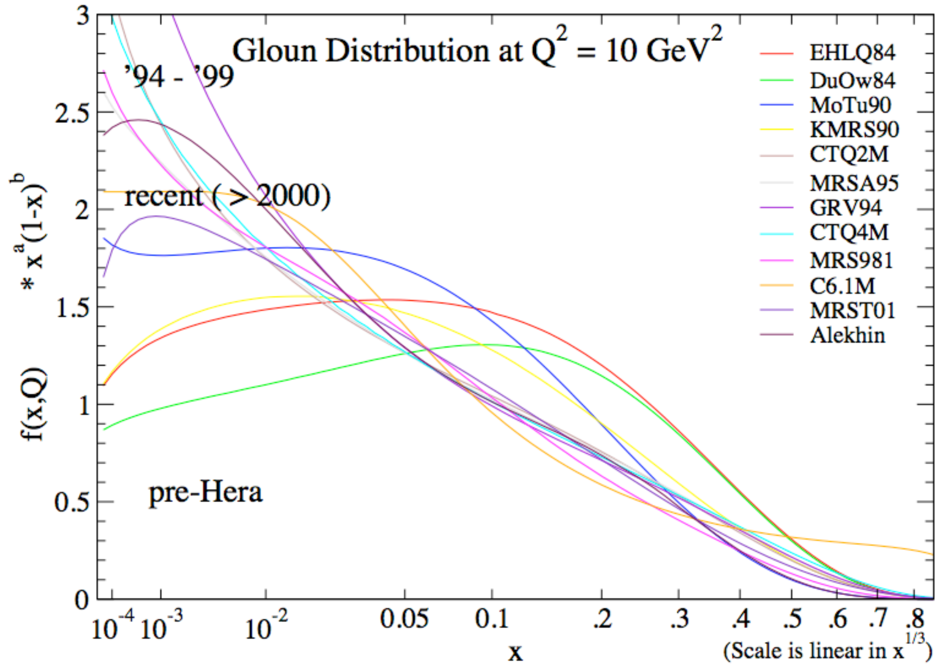
Parton Distributions pre-/post-HERA

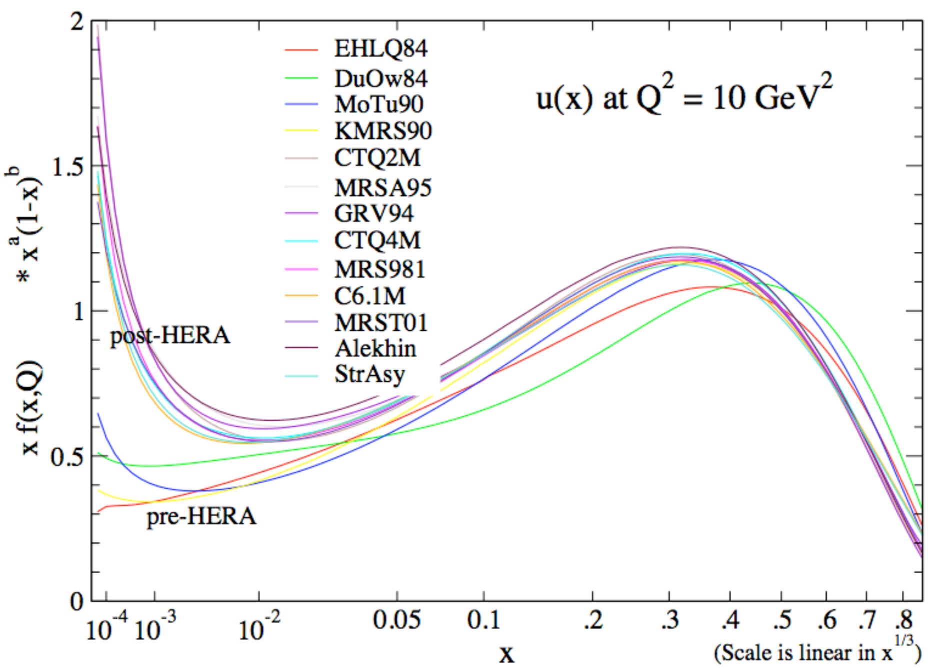
Nuclear beams and polarization are among the new machine capabilities at EIC,

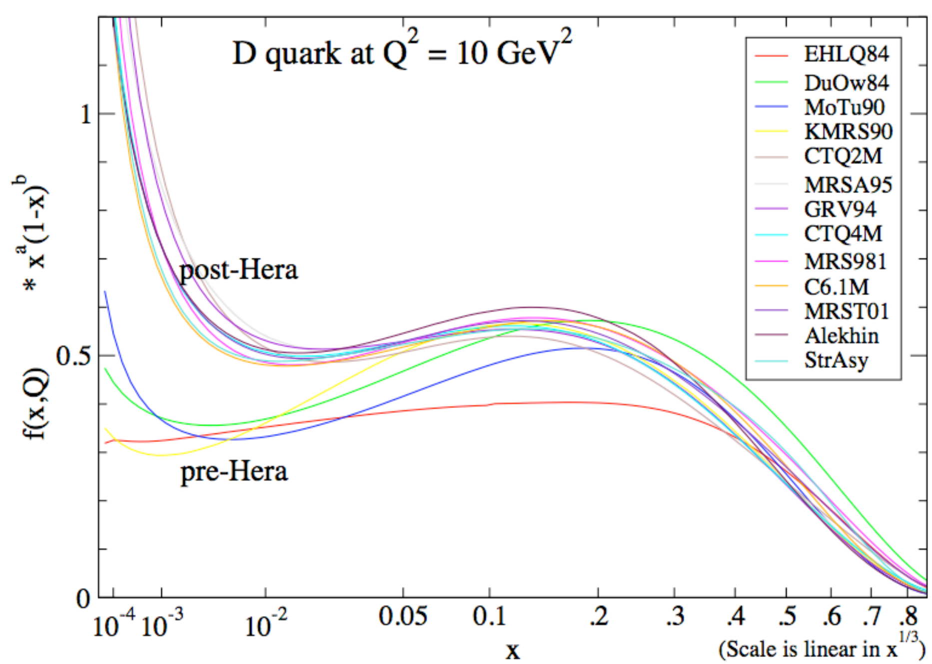
Which profound quantitative/conceptual impact(s) does this have?

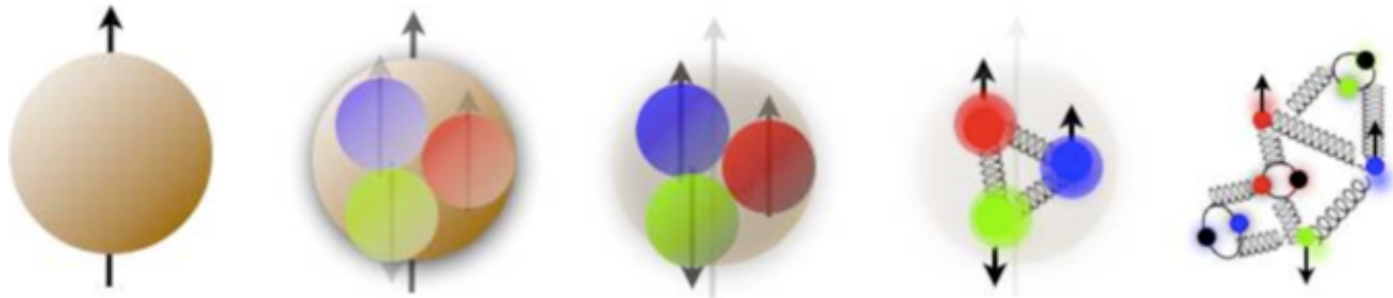
Luminosity and detector capability?

Figures reproduced from W.K. Tung, *"Status of Global QCD analysis and the Parton Structure of the Nucleon"*, 2004.









$A^{+}=0$ gauge version

Jaffe, Manohar; Ji; …

$$\frac{1}{2}\hbar = \langle P, \frac{1}{2} | J^z_{\mathrm{QCD}} | P, \frac{1}{2} \rangle = \sum_q \frac{1}{2} S^z_q + S^z_g + \sum_q L^z_q + L^z_g$$

sum of quark polarizations

$$S_g = \int_0^1 \Delta g(x) dx$$

gluon polarization

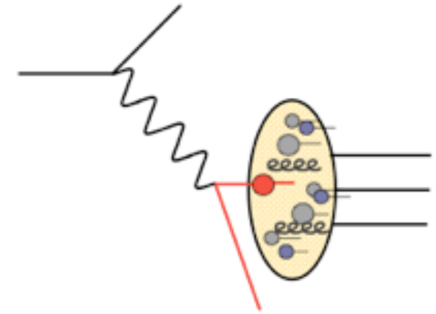
orbital angular momenta

Determining moments from measurements intrinsically entails extrapolation; reasons to measure over wide and resolved *x* are practical, besides of fundamental interest.

EIC - Physics of Helicity Distributions

Familiar 1-photon exchange cross section,

$$\frac{d^3\sigma}{dx\, dQ^2\, d\phi} = \frac{\alpha^2}{Q^4}\left(\frac{Q}{2MEx}\right)^2 l_{\mu\nu}W^{\mu\nu}$$



but with spins,

$$\frac{d^2\sigma}{dx\, dQ^2} = \frac{4\pi\,\alpha^2}{Q^4}\left[F_1\, y^2 + F_2\frac{1}{x}\left(1 - y - \frac{Mxy}{2E}\right) \pm g_1\, y\left(y - 2 + \frac{Mxy}{E}\right) \pm g_2\frac{2Mx}{E}\right]$$

Parton interpretation:

$$F_1(x) = \frac{1}{2}\sum_q e_q^2 q(x),$$

$$F_2(x) = x\sum_q e_q^2 q(x),$$

Quarks are spin-1/2 - Callan-Gross relation; gluons break this relation - F_L (or R)

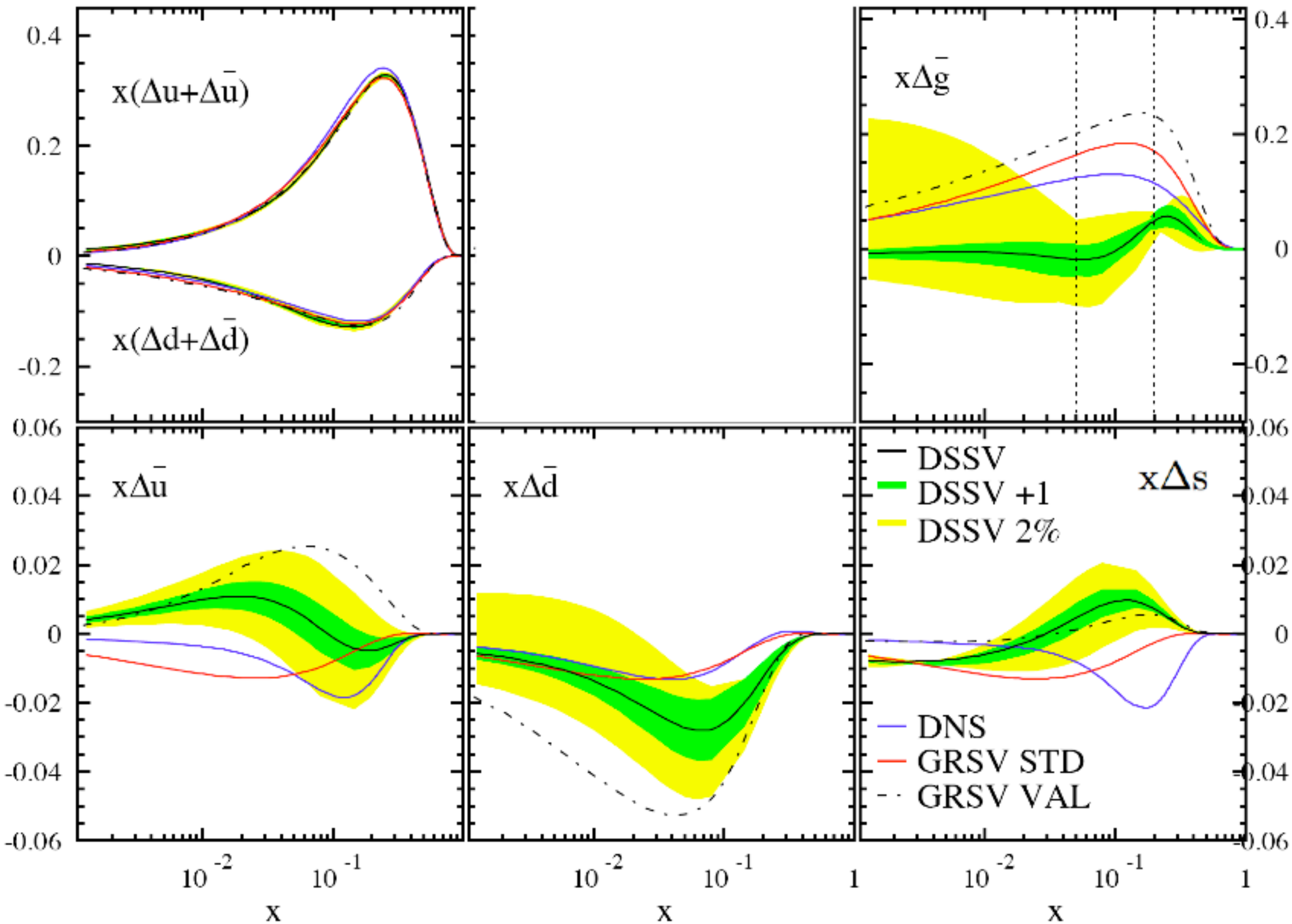
$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x),$$

g_1 tells us about quark spins

$$g_2(x) = 0,$$

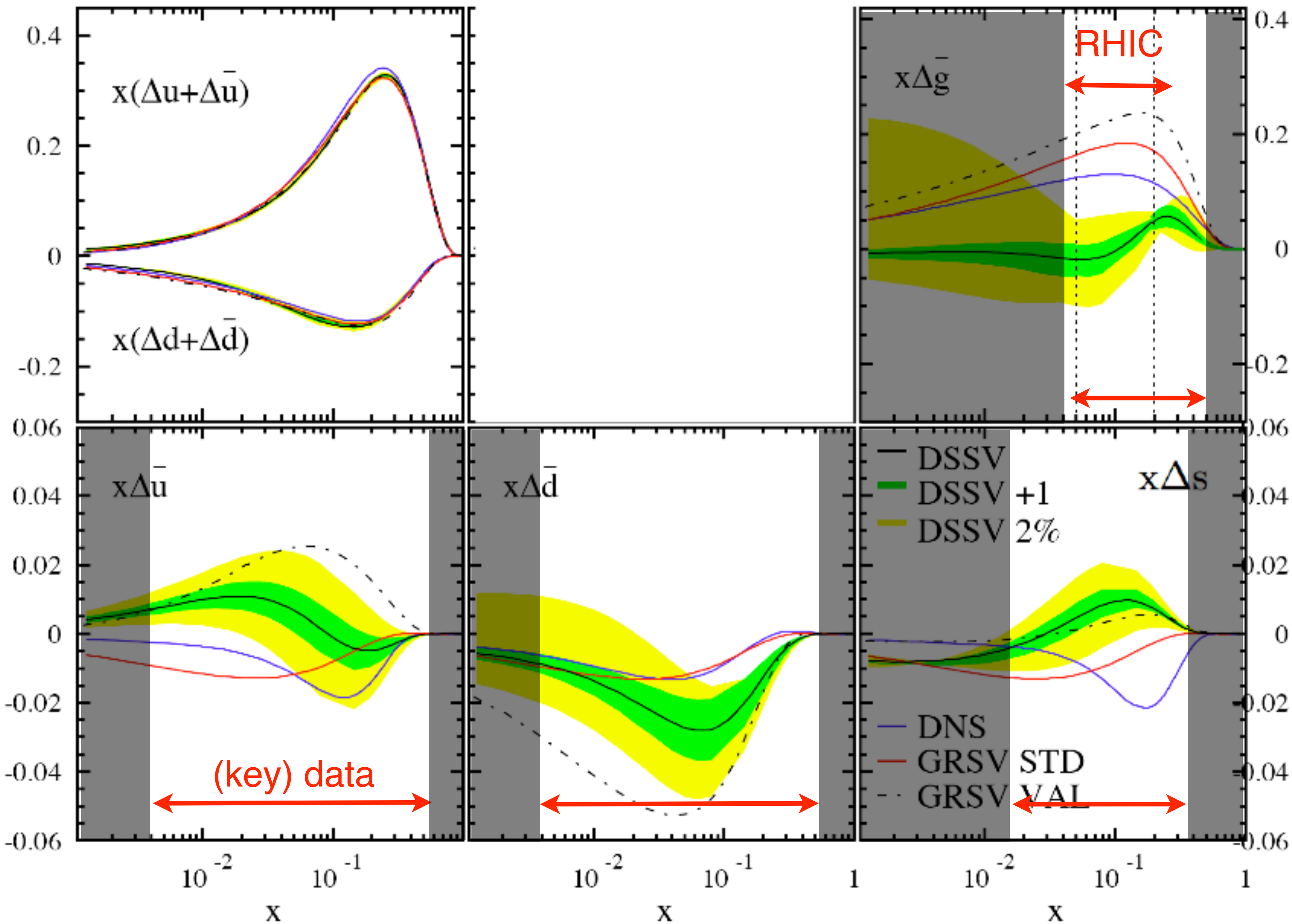
Familiar factorization, evolution with spin...

Helicity Distributions - Today



DSSV, Q^2 = 10 GeV^2

Helicity Distributions - Today

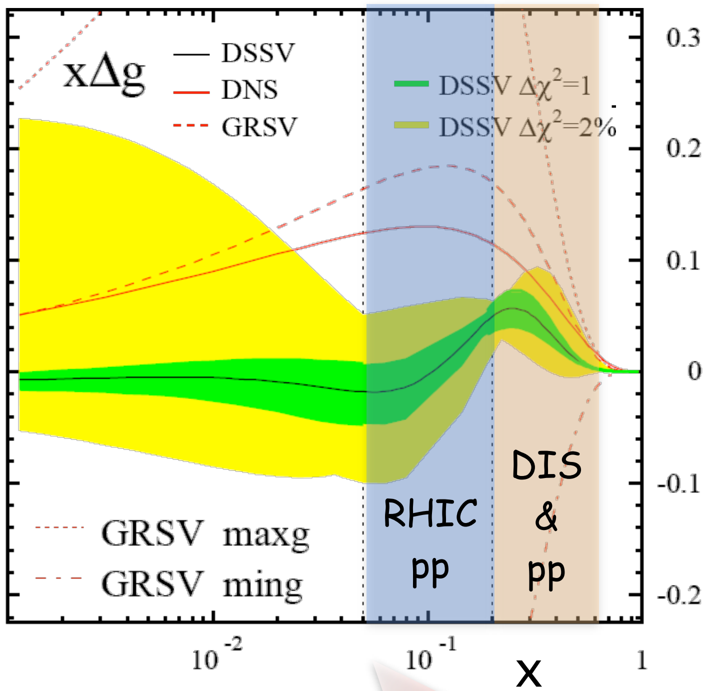


DSSV, Q^2 = 10 GeV^2

Helicity Distributions - Gluons

Gluon Polarization

current status:

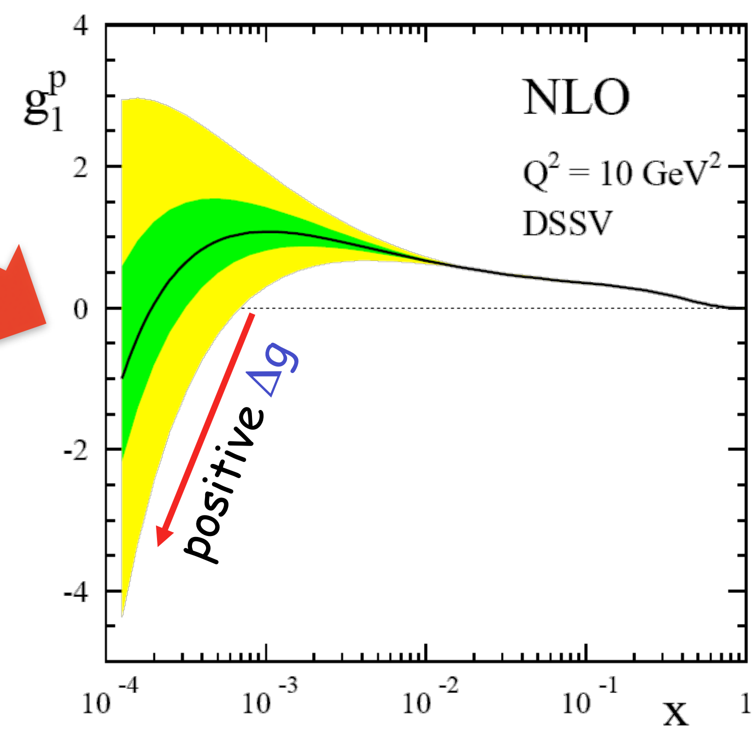


DSSV global fit
de Florian, Sassot, Stratmann, Vogelsang

- low x behavior unconstrained
- no reliable error estimate for 1st moment $\int_0^1 dx\, \Delta g(x,Q^2)$ (entering spin sum rule)
- find $\int_{0.05}^{0.2} dx\, \Delta g(x,Q^2) \approx 0$

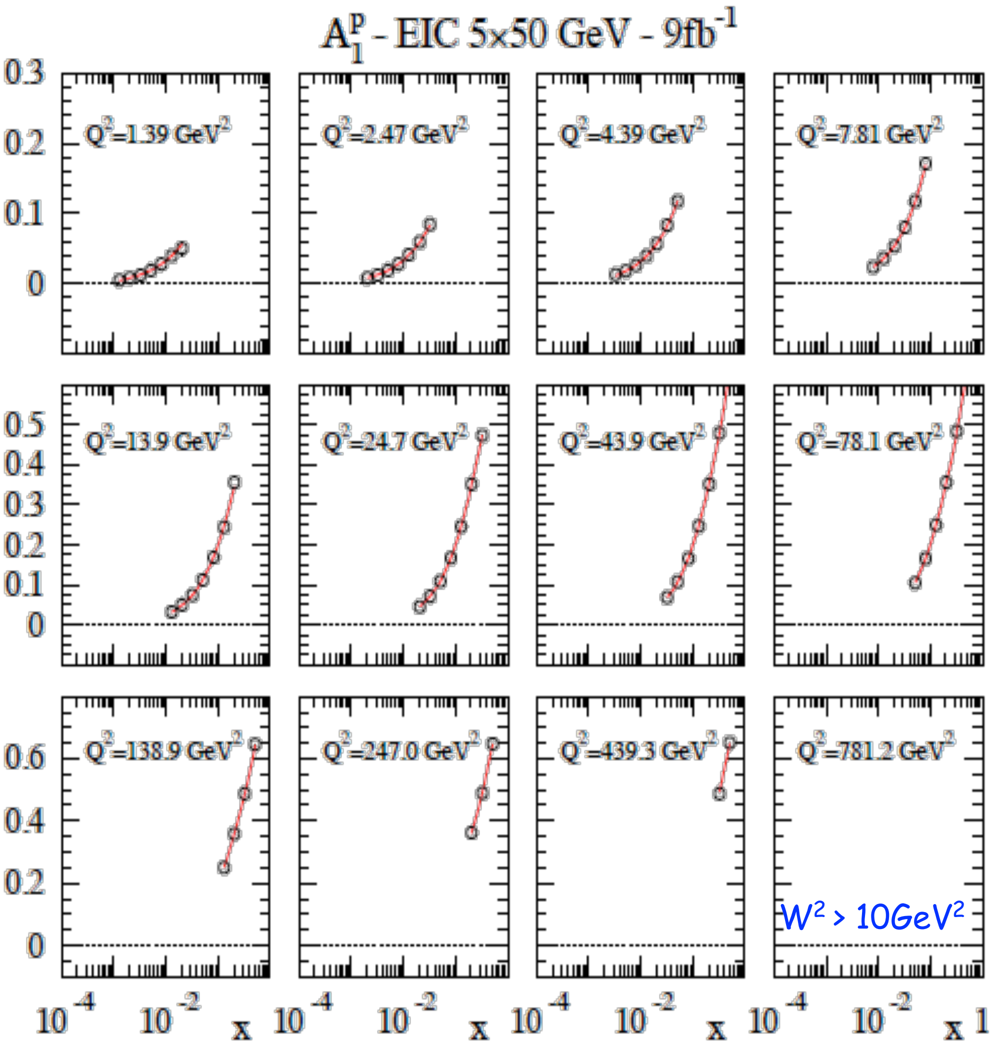
pQCD scaling violations

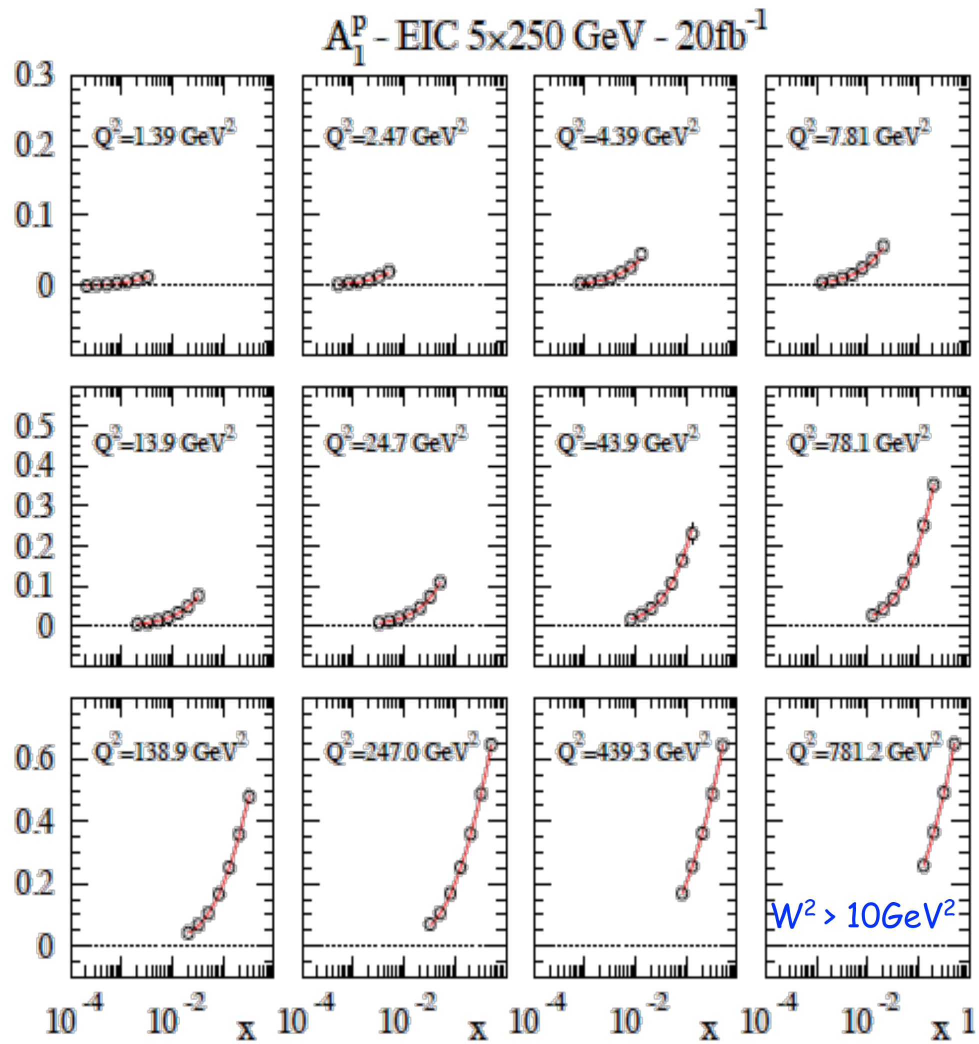
$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$



Gluon Polarization

Evaluate impact with realistically simulated pseudo-data in global fits:





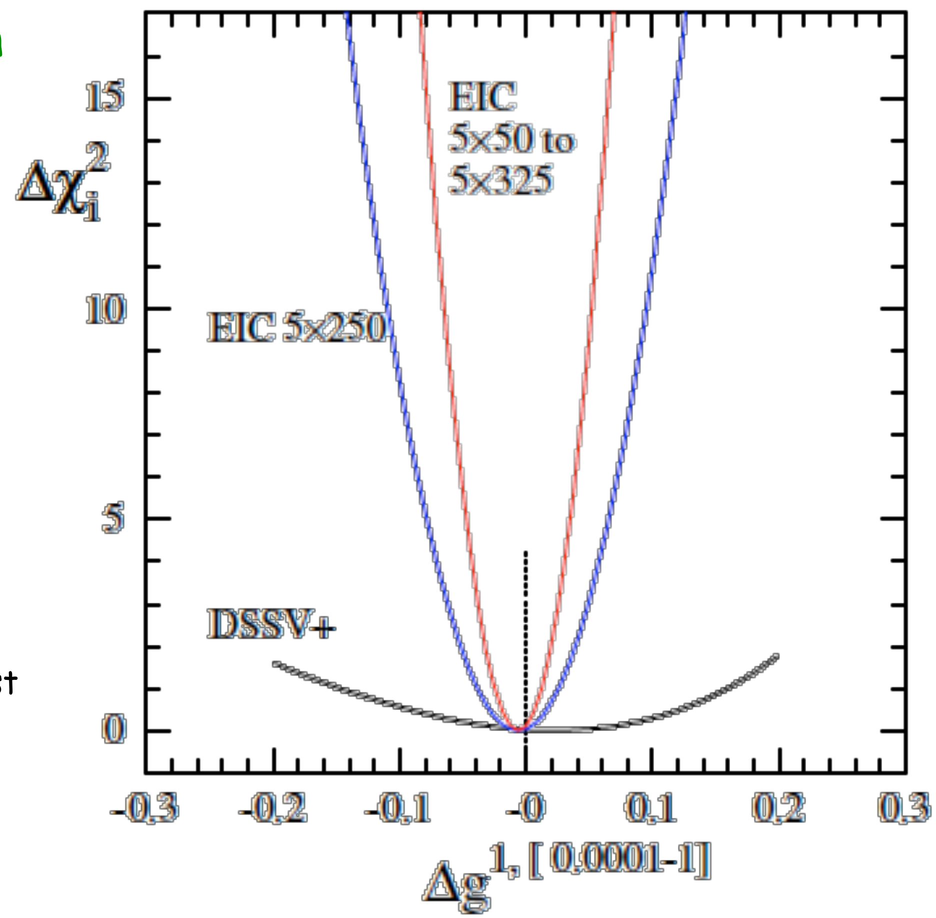
DIS statistics "insane" after ≈ 1 month of running (errors MUCH smaller than points in plots)

measurements limited by systematics – true for most of ep case

Gluon Polarization

how effective are scaling violations already at stage-1 (recall $x_{min} \approx 1.6\times10^{-4}$)

Sassot, Stratmann
also Taneja



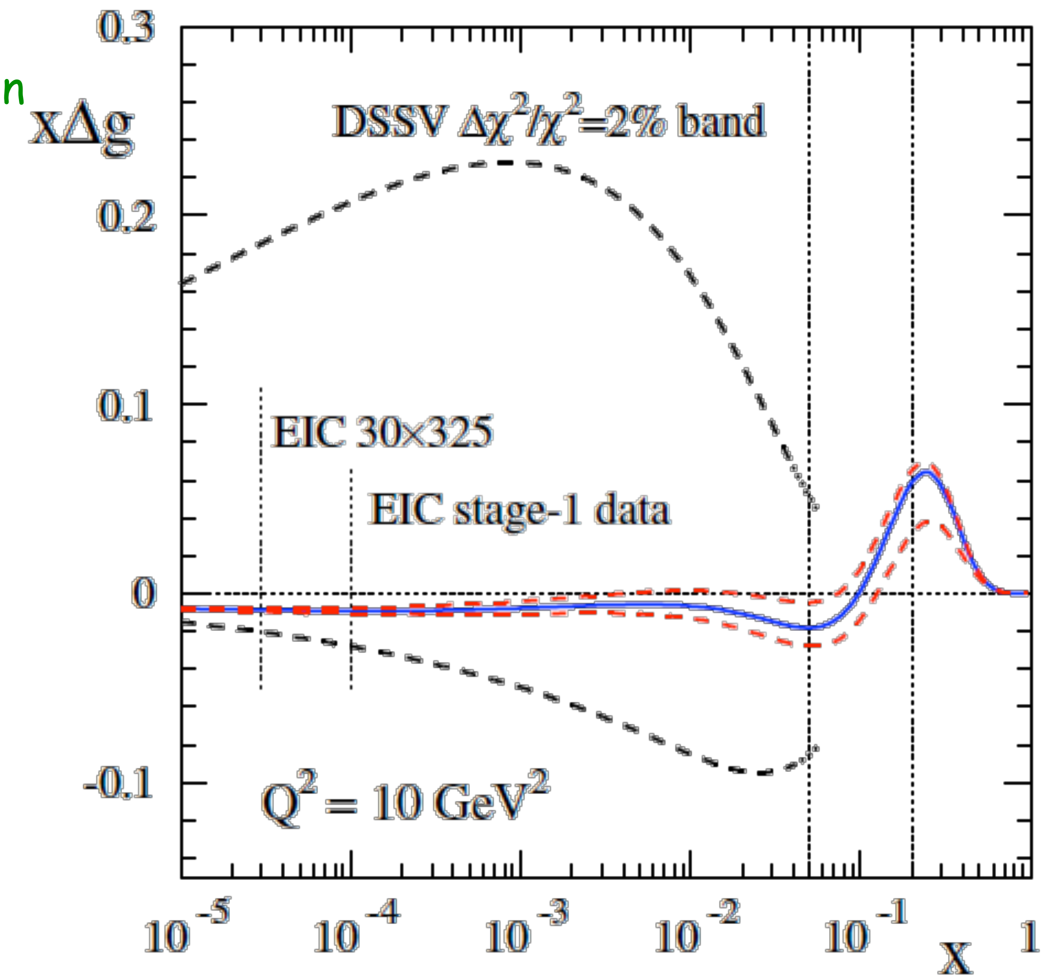
DSSV+ includes also latest COMPASS (SI)DIS data (no impact on DSSV Δg)

- with 30x325 one can reach down to $x \approx 3\times10^{-5}$ (impact needs to be quantified)

Gluon Polarization

what about the uncertainties on the x-shape ...

Sassot, Stratmann
also Taneja



golden measurement

✓ unique
✓ feasible
✓ relevant

- even with flexible DSSV x-shape we can now determine $\int_0^1 dx\, \Delta g(x,Q^2)$ to about ± 0.07
- work in progress: try weird x-shapes below x = 10^{-4} to improve/check error estimate

Some Other Options with Inclusive Structure Functions

- Bjorken sum: $$\int_0^1 dx\,\left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] = \frac{1}{6} C_{\mathrm{Bj}}\left[\alpha_s(Q^2)\right]\; g_A$$
  - C_{Bj} known to $O(\alpha_s^4)$ Kodaira; Gorishny, Larin; Larin, Vermaseren; Baikov, Chetyrkin, Kühn, ...
  - correction is typically ~8% of value and has, hence, not yet been observed *directly*.
  - polarized deuteron beam with proton and neutron tagging seems ideal, but unrealistic.
  - experimental challenge: effective neutron beam (^{3}He), precision hadron polarimetry, …

- Strong coupling from pQCD fit of scaling violations?

  to polarized and unpolarized data simultaneously?

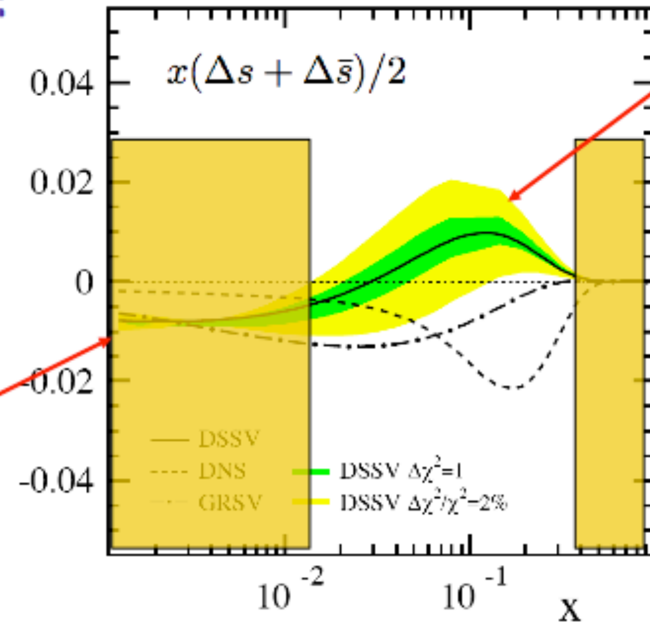
Helicity Distributions - Quarks

Strange Quark Polarization

Insight in strange quark polarization is *far* from satisfactory.

W. Vogelsang at INT:

- strangeness :



driven by SIDIS (kaons ... fragm. fcts.?)

driven by SU(3) (3F-D)

$$\int_{0.001}^{1} dx\, \Delta s(x) = -0.006 \pm 0.01 \qquad (\Delta\chi^2 = 1)$$

$$\int_{0}^{1} dx\, \Delta s(x) = -0.057 \pm ?$$

using F,D and SU(3)

?

$$\int_{0.001}^{1} dx \Delta\Sigma = 0.366 \pm 0.016 \qquad \int_{0}^{1} dx \Delta\Sigma = 0.242 \pm ?$$

Strange Quark Polarization

Insight in strange quark polarization is *far* from satisfactory.

E. Leader et al, “A Possible Solution to the Strange Quark Polarization Puzzle?”, arXiv:1103.5979

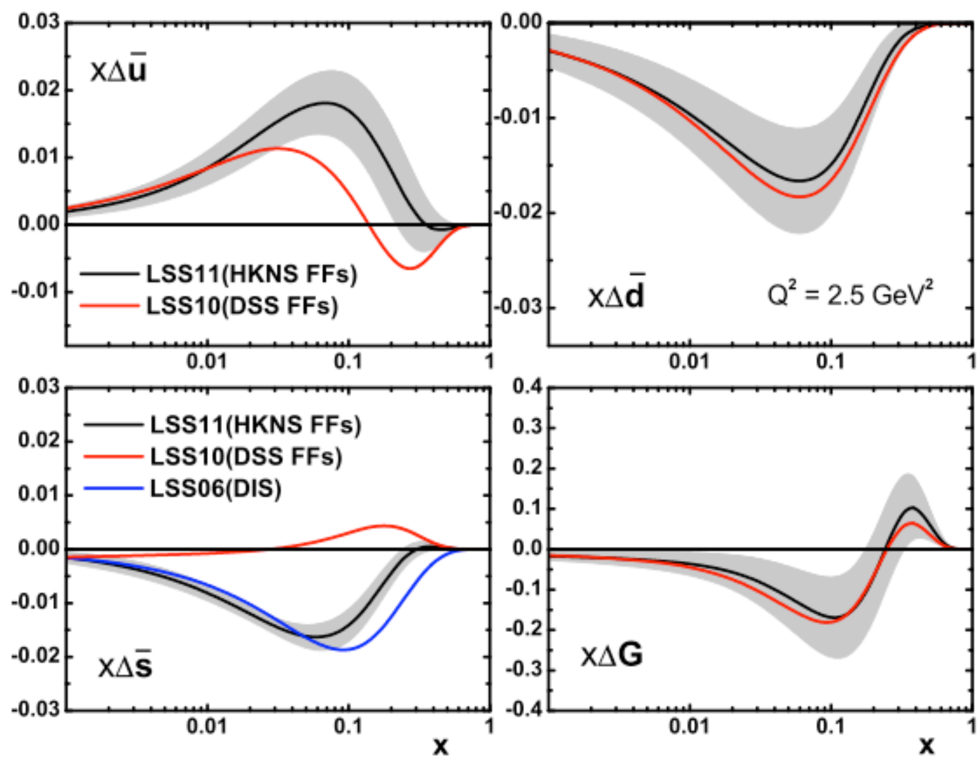


Figure 4: Comparison between NLO LSS’11(HKNS FFs) and LSS’10(DSS FFs) sea quark and gluon polarized PDFs at $Q^2 = 2.5\ GeV^2$. The blue curve corresponds to $x(\Delta s(x) + \Delta\bar{s}(x))/2$ obtained from the pure DIS analysis [2].

Strange Quark Polarization

Insight in strange quark polarization is *far* from satisfactory.

COMPASS Collaboration, Phys.Lett. **B693**: 227 (2010):

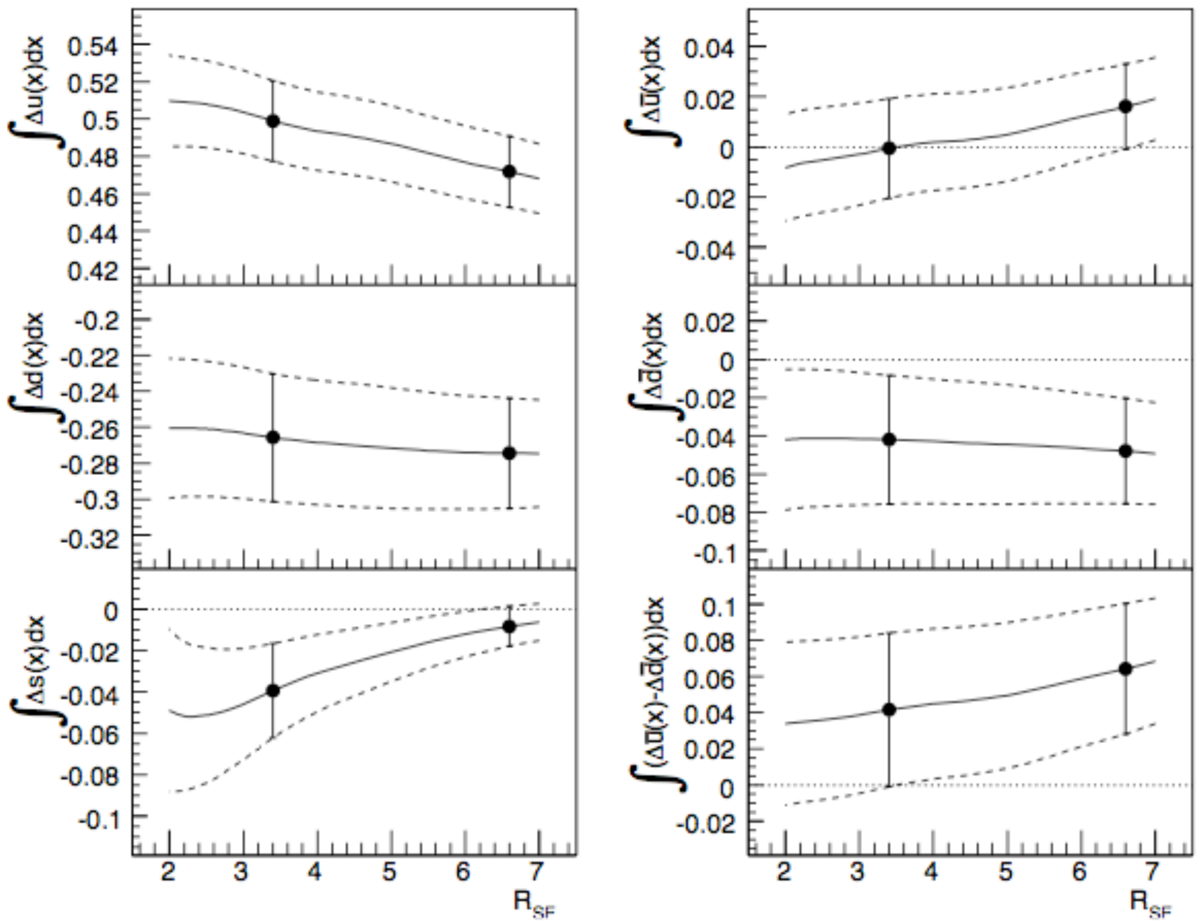
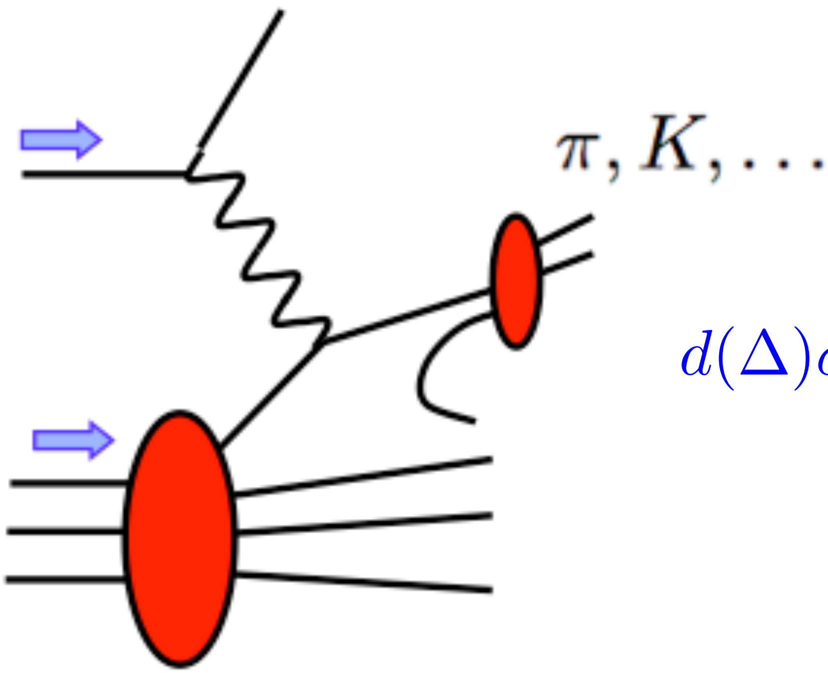


Fig. 5: Variation of the quark first moments Δu, $\Delta \bar{u}$, Δd, $\Delta \bar{d}$, Δs and $\Delta \bar{u} - \Delta \bar{d}$ integrated over the interval $0.004 < x < 0.3$ as a function of the ratio R_{SF} of $\bar{s}$ and u quark fragmentation functions into K^+. The ratio R_{UF} is varied linearly from 0.13 at $R_{SF} = 6.6$ to 0.35 at $R_{SF} = 3.4$. The left and right black points indicate the values obtained using the EMC [32] and the DSS [30] kaon fragmentation functions, respectively.

Strange Quark Polarization

Insight in strange quark polarization is *far* from satisfactory.

Clear call for EIC to measure, *simultaneously*, spin-dependent and spin-independent DIS production cross sections for many identified hadrons; π^+, π^-, K^+, K^-, ...



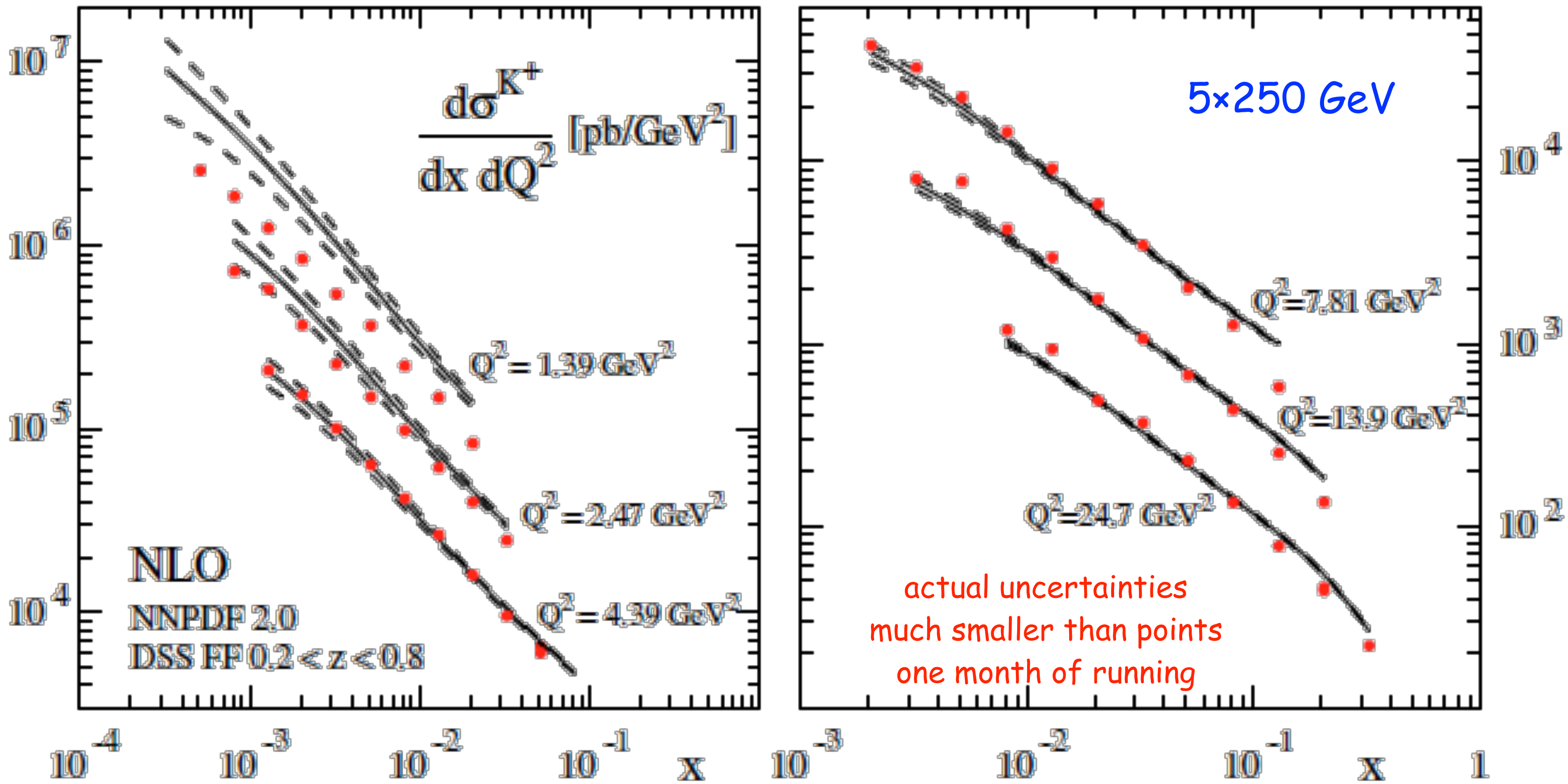
$$d(\Delta)\sigma^H \sim \sum_{q=u,\bar{u},\ldots,\bar{s}} (\Delta)q(x,Q^2)\; D_q^H(z,Q^2)$$

Towards Strange Quark Polarization - Charged Kaons

Aschenauer, Stratmann

compute K^+ yields at NLO with 100 NNPDF replicas

z integrated to minimize FF uncertainties (work in progress)

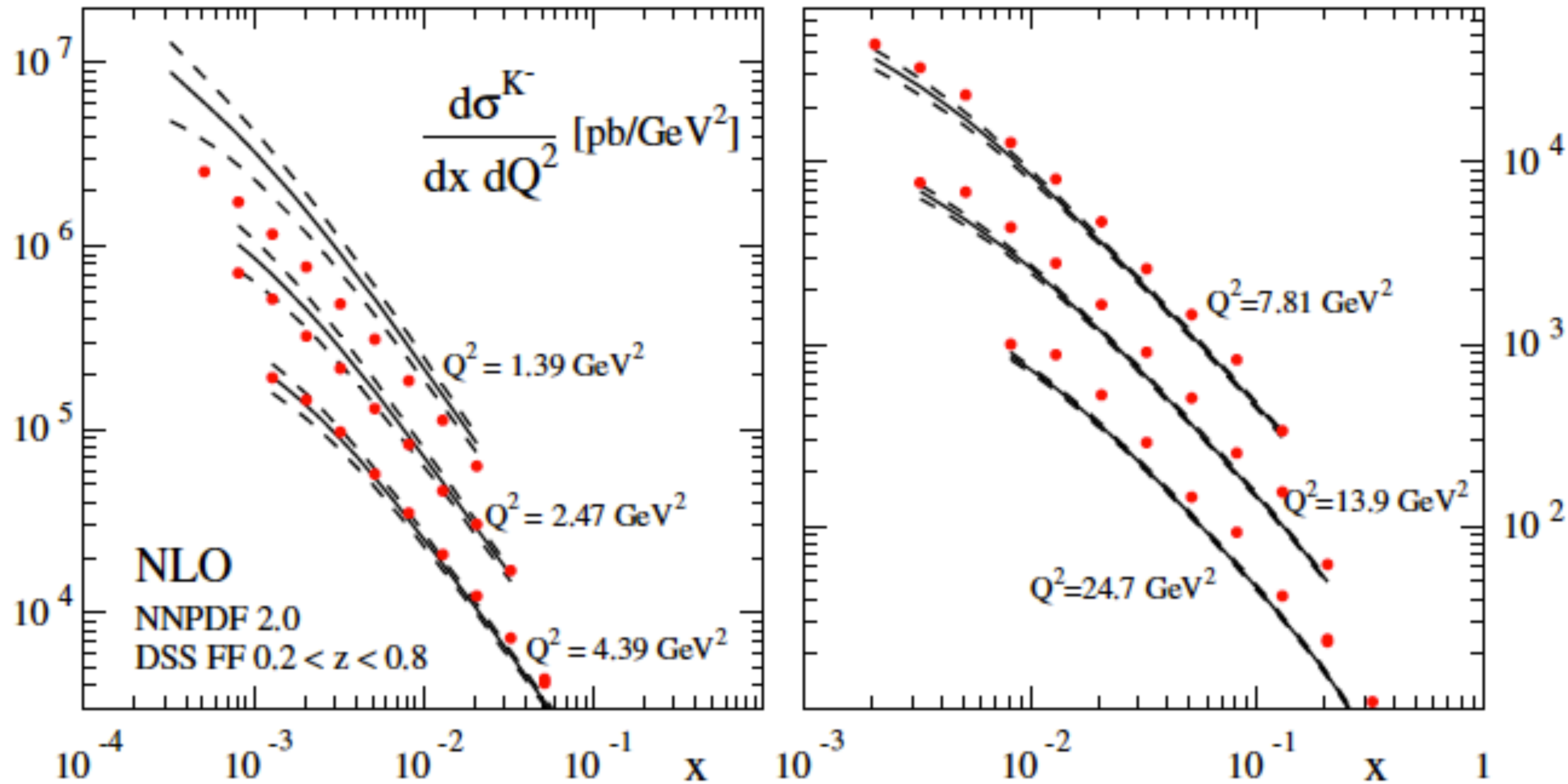


PYTHIA agrees very well (despite **very** different hadronization model)

--> confidence that we can use MC to estimate yields & generate toy data

Towards Strange Quark Polarization - Charged Kaons

how about K⁻ (relevant for $s - \bar{s}$ separation)

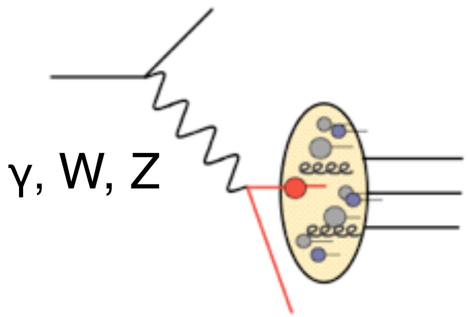


next step: assess impact of data on PDFs with "reweighting method" Giele, Keller; NNPDF
(using full set of stage-1 energies: 5×50 – 5×325)

in progress: include also $\pi^{\pm}$; polarized SIDIS and impact on global fit

Electroweak Structure Opportunities

Inclusive Electroweak Structure Functions



at high enough Q^2 electroweak probes become relevant

- **neutral currents** (γ, Z exchange, γZ interference)
- **charged currents** (W exchange)

parameterized with structure functions that probe combinations of PDFs *different* from photon exchange

Flavor decomposition without SIDIS, e-w couplings

hadron-spin averaged case: several textbook measurements from HERA - precision

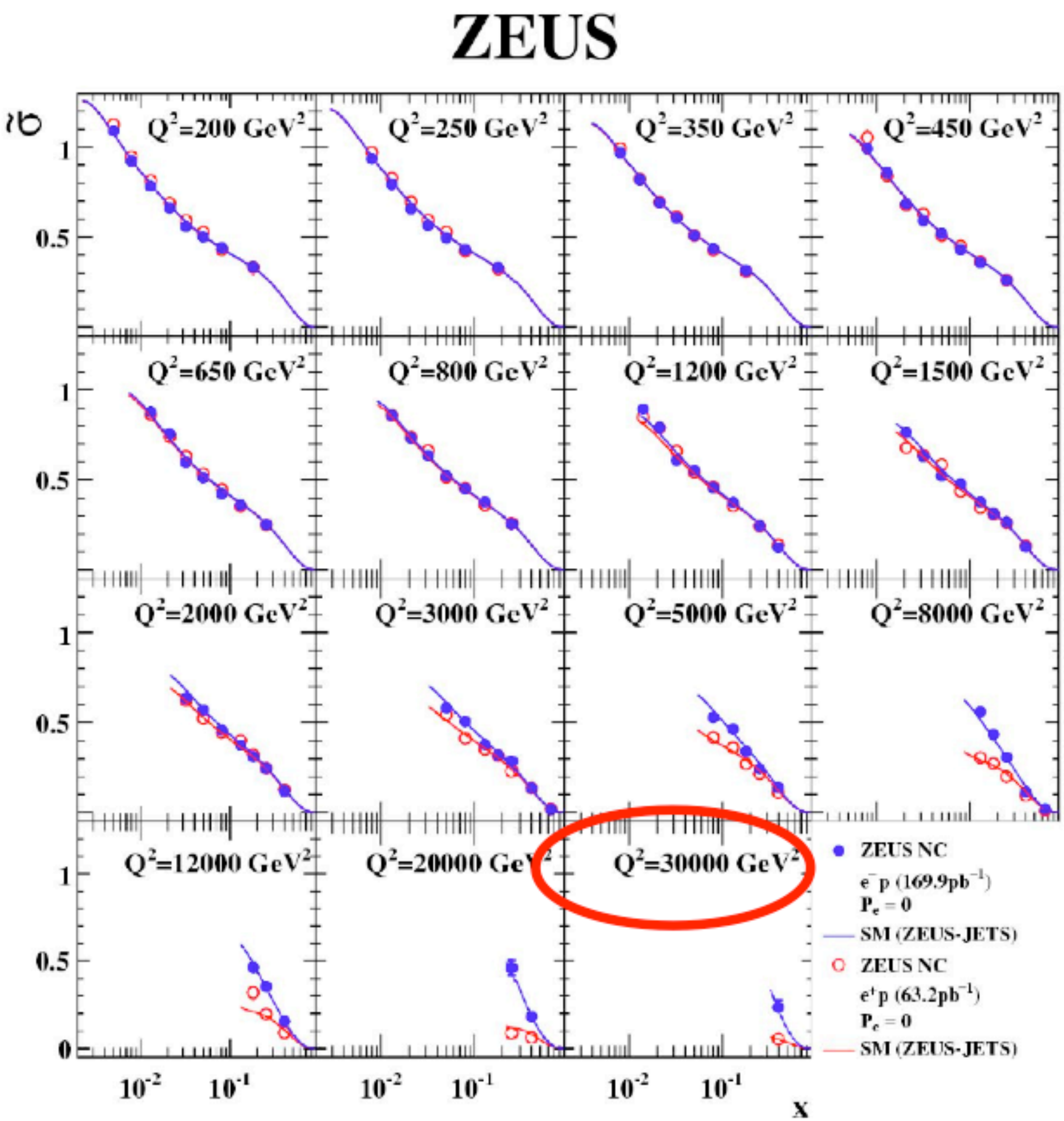
hadron-spin difference: unique to a (polarized) EIC

contains
e-w propagators
and couplings

Wray; Derman; Weber, MS, Vogelsang;
Anselmino, Gambino, Kalinowski;
Blumlein, Kochelev; Forte, Mangano, Ridolfi; ...

$$\frac{d\Delta\sigma^{e^{\mp},i}}{dx\,dy} = \frac{4\pi\alpha^2}{xyQ^2}\left[\pm y(2-y)x\hat{g}_1^i - (1-y)\hat{g}_4^i - y^2 x\hat{g}_5^i\right] \quad \mathrm{i} = \mathrm{NC}, \mathrm{CC}$$

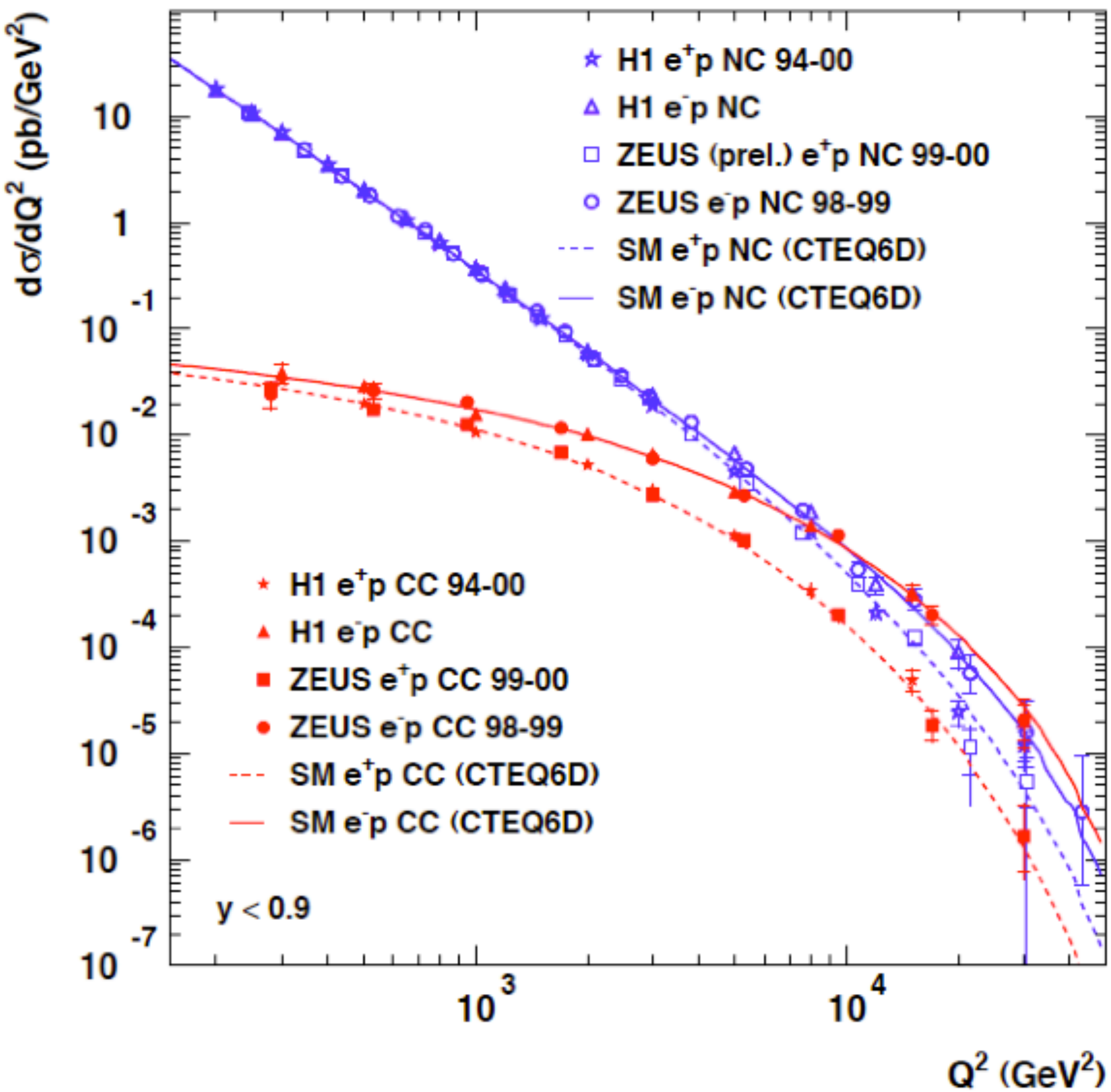
HERA - Onset of γ,Z interference



electron beam (unpol.)

positron beam (unpol.)

HERA - Neutral vs. Charged Current Interactions

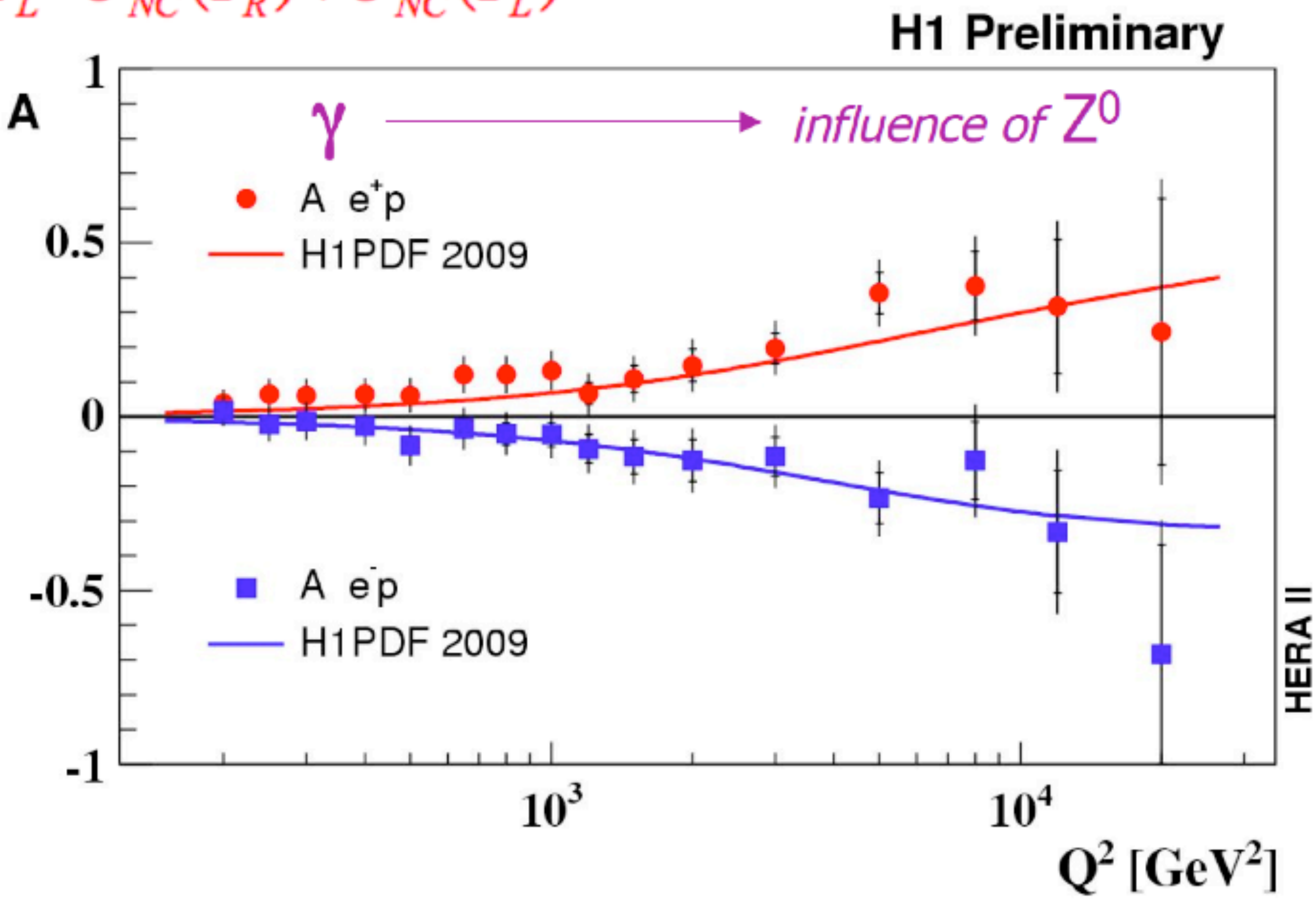


$$\sigma(e^- p) \simeq u$$

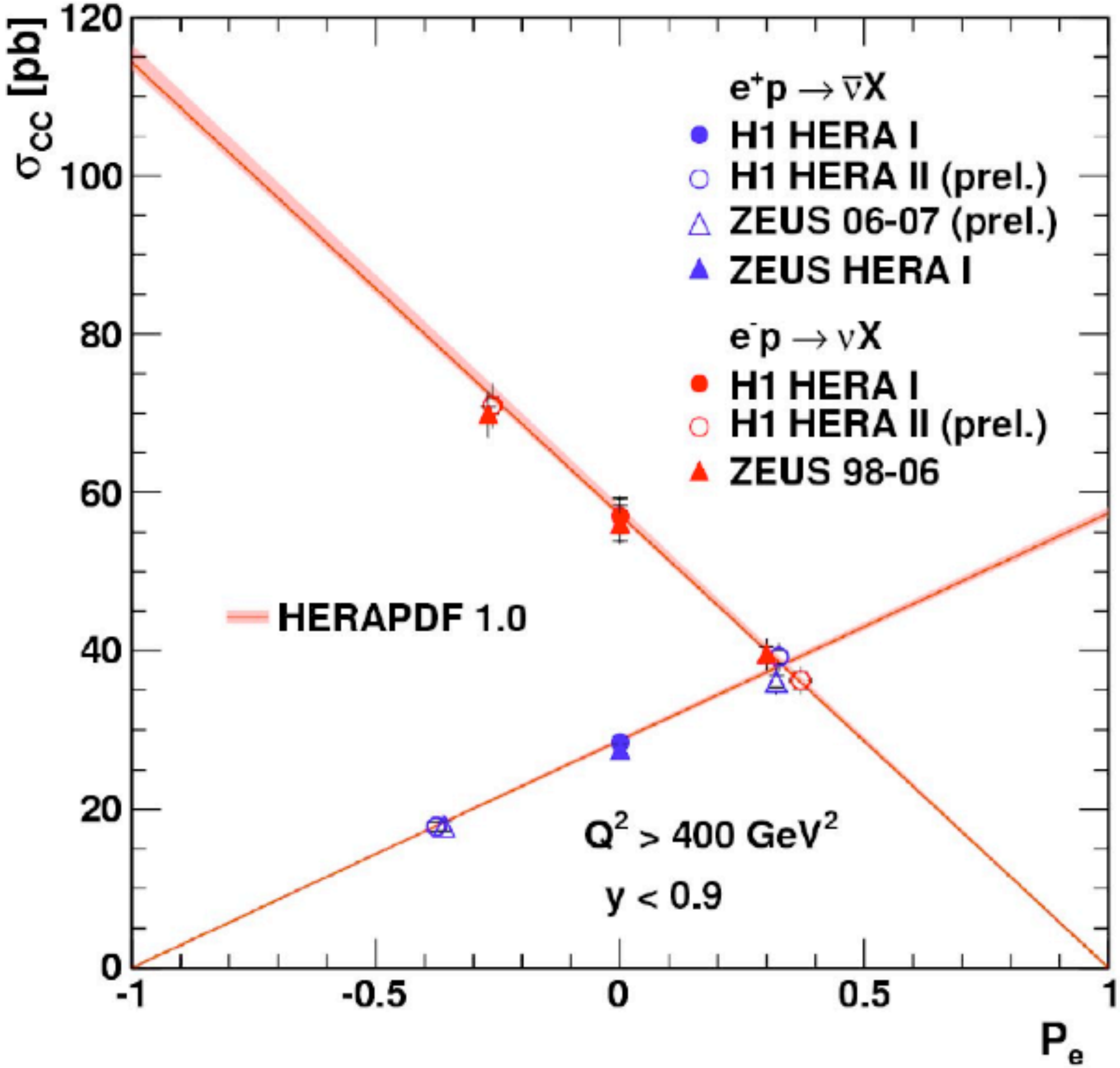
$$> \sigma(e^+ p) \simeq d$$

HERA - Polarized Lepton Beams

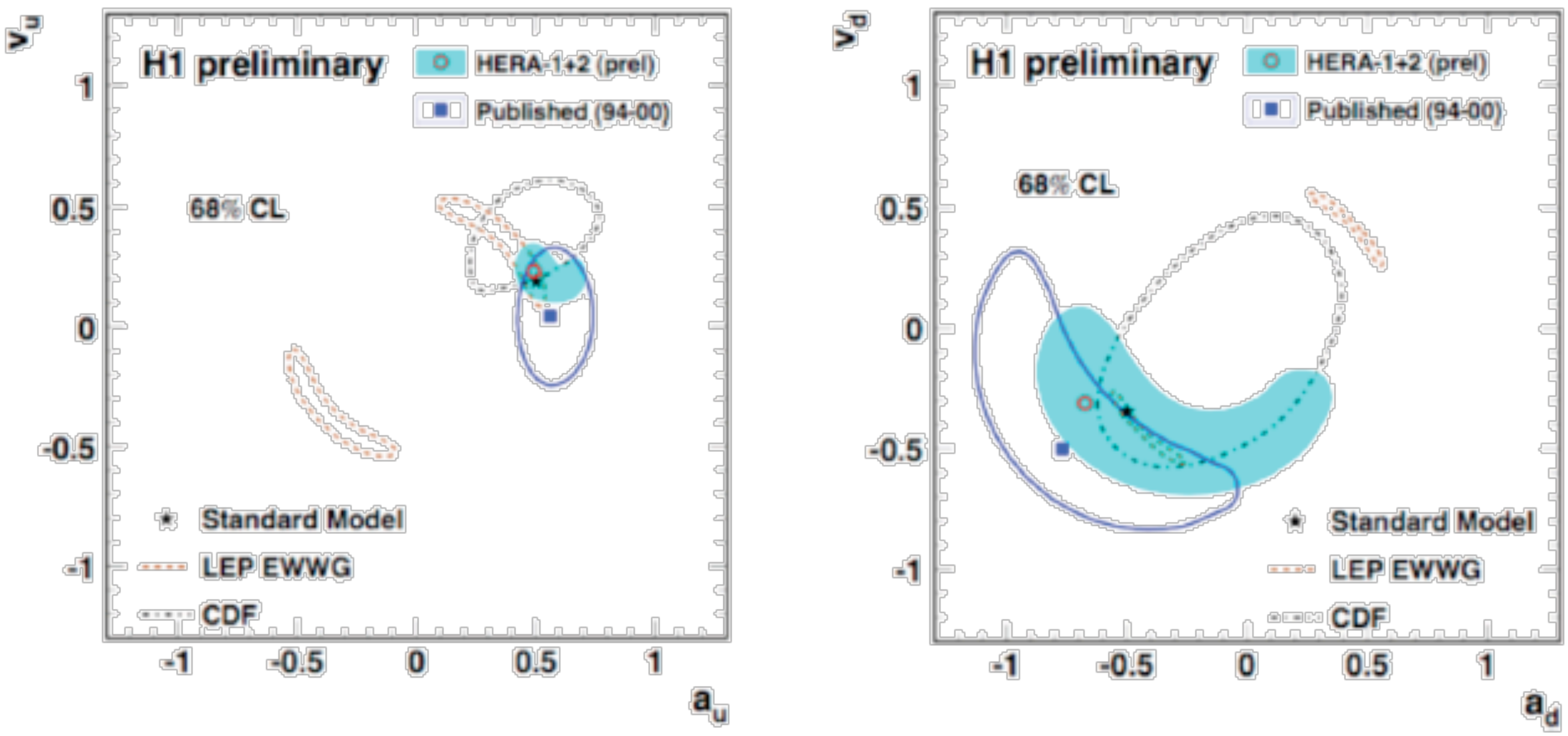
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}_{NC}(P_R) - \sigma^{\pm}_{NC}(P_L)}{\sigma^{\pm}_{NC}(P_R) + \sigma^{\pm}_{NC}(P_L)}$$



HERA - Polarized Lepton Beams



HERA - Couplings



a_q mainly constrained by $xF_3^{\gamma Z}$

v_q mainly constrained by F_2^Z

Open question: What would it take for an EIC to surpass this level of precision?

Inclusive Electroweak Spin Structure Functions

Neutral Current proton spin structure functions at parton-model level:

$$\left[g_1^{\gamma}, g_1^{\gamma Z}, g_1^{Z}\right] = \frac{1}{2}\sum_q \left[e_q^2, 2e_q g_V^q, (g_V^q)^2 + (g_A^q)^2\right] (\Delta q + \Delta \bar{q})$$

$$\left[g_5^{\gamma}, g_5^{\gamma Z}, g_5^{Z}\right] = \frac{1}{2}\sum_q \left[0, e_q g_A^q, g_V^q g_A^q\right] (\Delta q - \Delta \bar{q})$$

Charged Current proton structure functions at parton-model level:

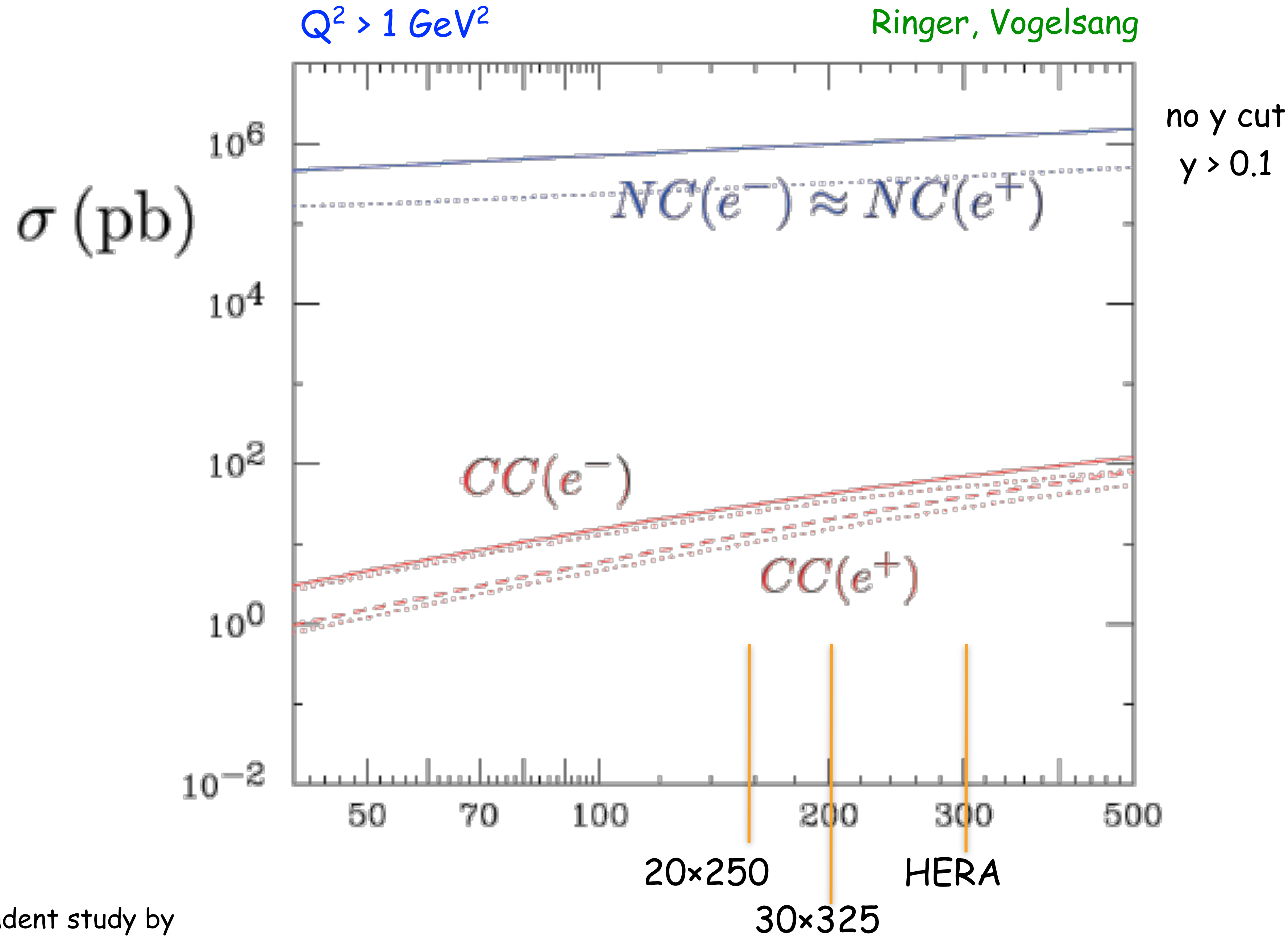
$$\begin{aligned}
g_1^{W^-} &= (\Delta u + \Delta \bar{d} + \Delta \bar{s} + \Delta c) \\
g_1^{W^+} &= (\Delta \bar{u} + \Delta d + \Delta s + \Delta \bar{c}) \\
g_5^{W^+} &= (\Delta \bar{u} - \Delta d - \Delta s + \Delta \bar{c}) \\
g_5^{W^-} &= (-\Delta u + \Delta \bar{d} + \Delta \bar{s} - \Delta c)
\end{aligned}$$

positron, neutron

- NLO QCD corrections available,
- can be incorporated in a global QCD analysis,
- enough combinations, at least in principle, for a fragmentation-free flavor separation.

de Florian, Sassot; MS, Vogelsang, Weber;
van Neerven, Zijlstra; Moch, Vermaseren, Vogt

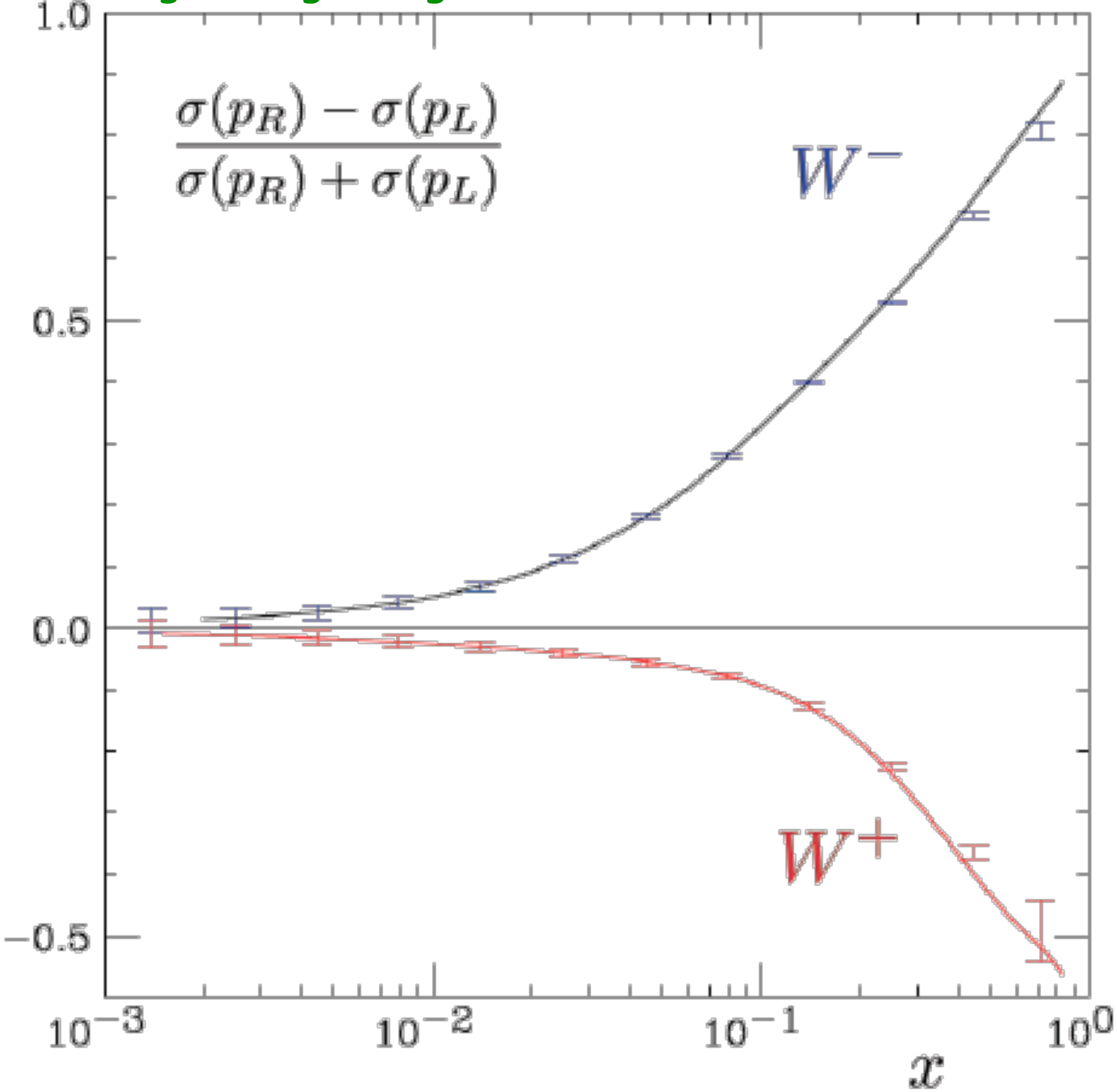
Inclusive Electroweak Structure Functions



2nd independent study by
Kumar, Riordan, Deshpande, Taneja, Paschke
detailed comparison under way

Inclusive Electroweak Structure Functions

Ringer, Vogelsang



20×250 GeV

$Q^2 > 1\ \mathrm{GeV}^2$

$0.1 < y < 0.9$

10 fb^{-1}

DSSV PDFs

very promising!

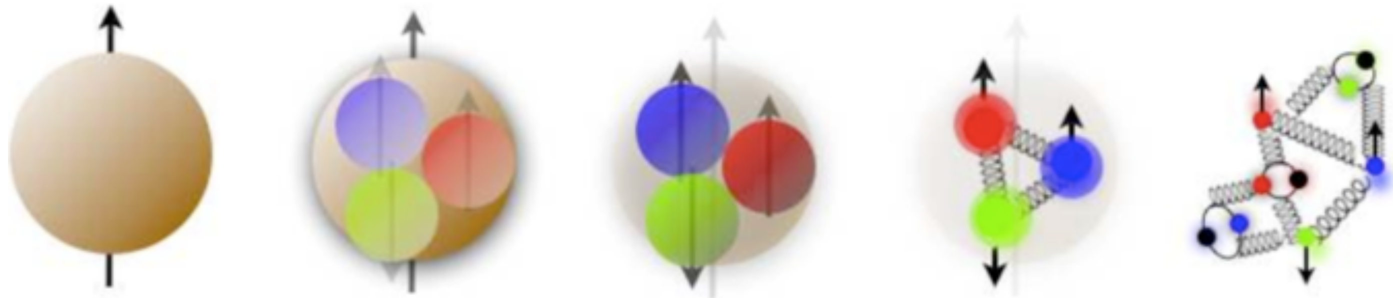
even doable with 5x250 GeV

impact on global fits to be quantified

W-SIDIS?

$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta\bar{d} + \Delta\bar{s})}{(u+c) + (1-y)^2(\bar{d}+\bar{s})} \quad A^{W^+} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta\bar{u} + \Delta\bar{c})}{(1-y)^2(d+s) + (\bar{u}+\bar{c})}$$

Towards Imaging



A^{+}=0 gauge version

Jaffe, Manohar; Ji; …

$$\boxed{\frac{1}{2}\hbar = \langle P, \frac{1}{2} | J^z_{\mathrm{QCD}} | P, \frac{1}{2} \rangle = \sum_q \frac{1}{2} S^z_q + S^z_g + \sum_q L^z_q + L^z_g}$$

$$S_g = \int_0^1 \Delta g(x)\, dx$$

sum of quark polarizations

gluon polarization

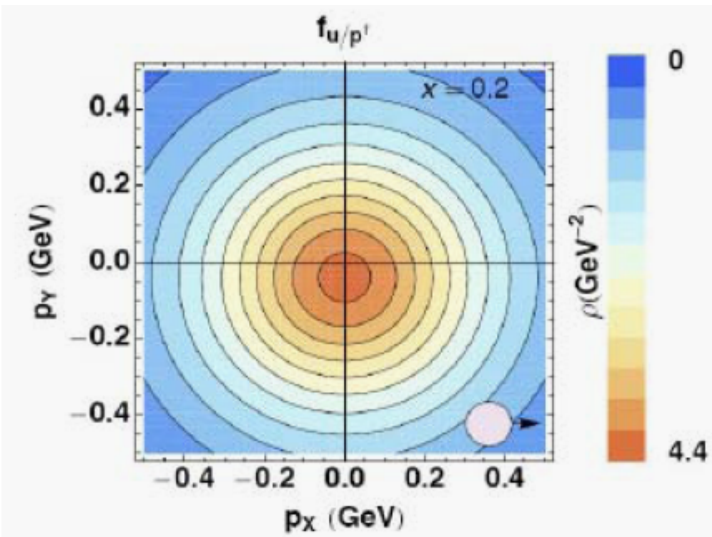
orbital angular momenta

Determining moments from measurements intrinsically entails extrapolation; reasons to measure over wide and resolved *x* are practical, besides of fundamental interest.

Towards Imaging - Two Approaches

TMDs

2+1 D picture in **momentum space**

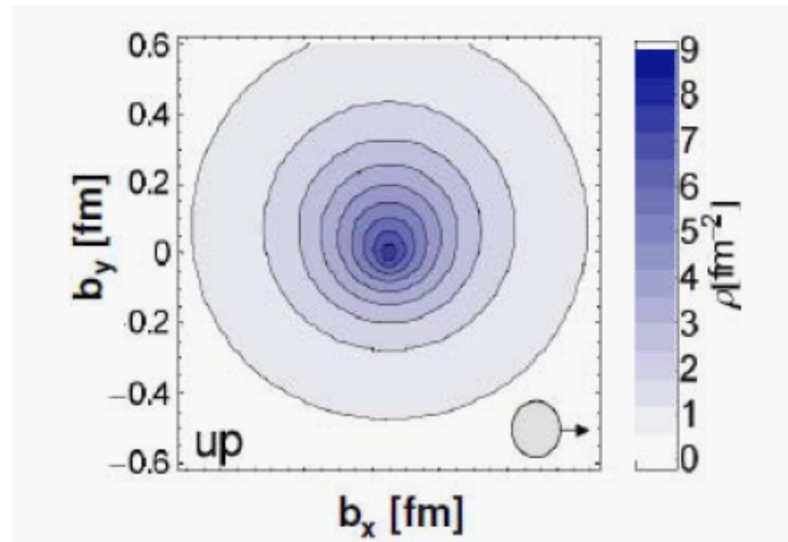


Bacchetta, Conti, Radici

- intrinsic transverse motion
- spin-orbit correlations = indicator of OAM
- non-trivial factorization
- accessible in SIDIS (and at RHIC)

GPDs

2+1 D picture in **impact-parameter space**



QCDSF collaboration

- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- DVCS, exclusive vector-meson production

no direct, model-independent direct relation known between TMDs and GPDs

Towards Imaging - TMDs in SIDIS

- many observables possible in lp -> lhX if intrinsic k_T included and Φ kept

  e.g. “left-right asymmetries” in the direction of produced hadron

- seen at HERMES and COMPASS (but mainly valence quark region & large uncertainties)

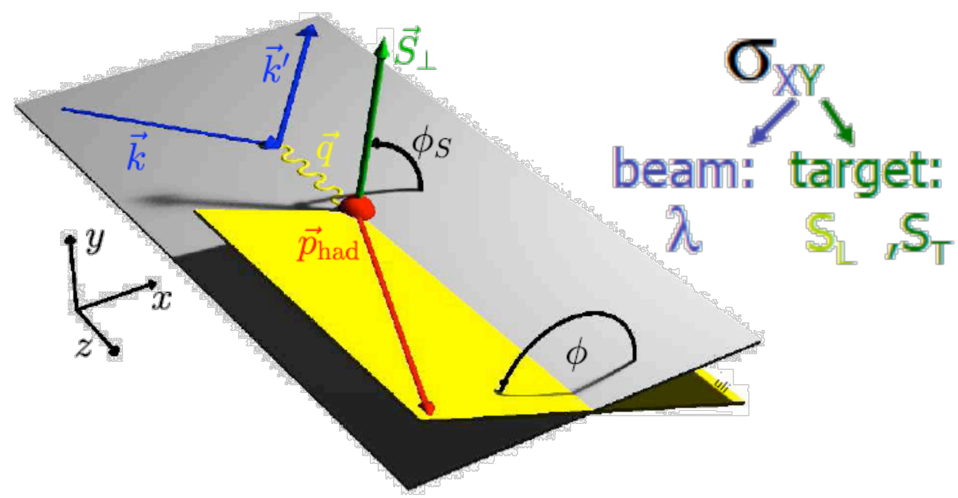
SIDIS cross section:

Kotzinian; Mulders, Tangermann; Boer, Mulders. ...

$$d\sigma^h(x,Q^2,z,P_T^h,\phi,\phi_S,\lambda) = d\sigma_{UU} + \cos 2\phi\, d\sigma_{UU} + S_L \sin 2\phi\, d\sigma_{UL} + \underbrace{\boxed{\lambda S_L d\sigma_{LL}}}_{\Delta q \otimes D}$$

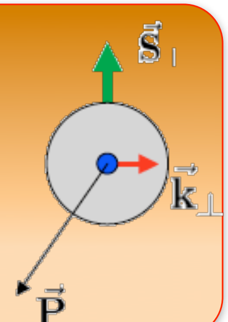
$$+S_T\left[\sin(\phi+\phi_S)d\sigma_{UT} + \underbrace{\boxed{\sin(\phi-\phi_S)d\sigma_{UT}}}_{f_{1T}^{\perp}\otimes D} + \sin(3\phi-\phi_S)d\sigma_{UT}\right]$$

$$+\lambda S_T \cos(\phi-\phi_S)d\sigma_{LT} + \frac{1}{Q}\cdots$$



$f_{1T}^{\perp}\otimes D$ **“Sivers effect”**

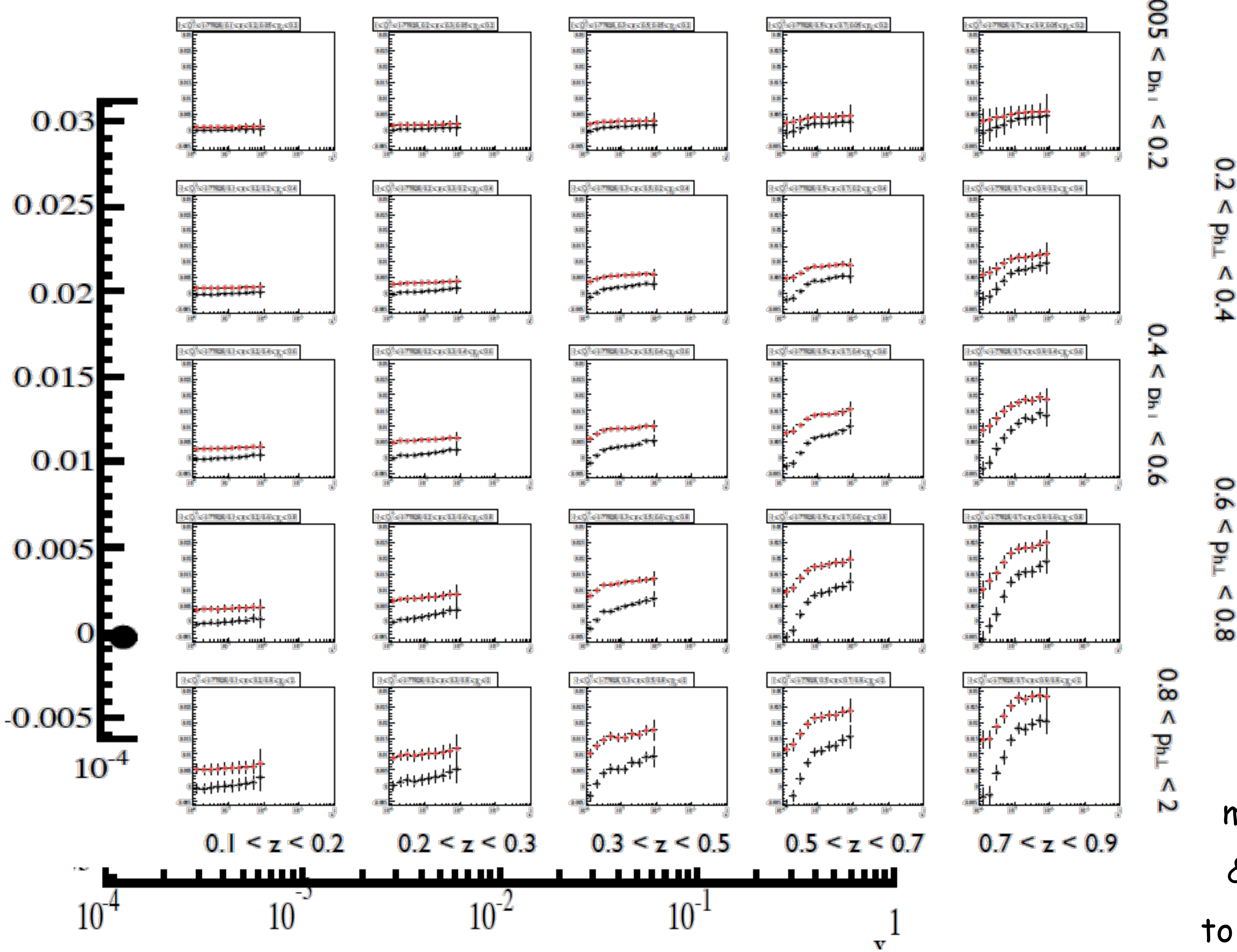
correlation of transverse spin of proton with k_T of unpolarized quark



Sivers TMD @ eRHIC: 1st feasibility study

T. Burton

$1 < Q^2 < 1.78$ GeV^2 +ve Sea No sea π^+



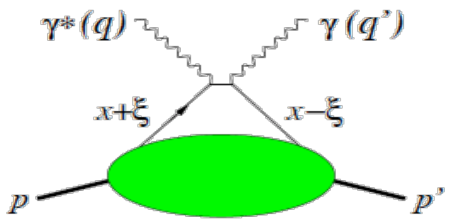
5 x 250 GeV

20 fb^{-1}

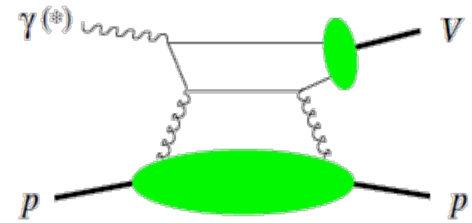
multi-dim. binning & Q^2 values up to to 100 GeV^2 possible

Towards Imaging - GPDs

need to measure & study exclusive processes:

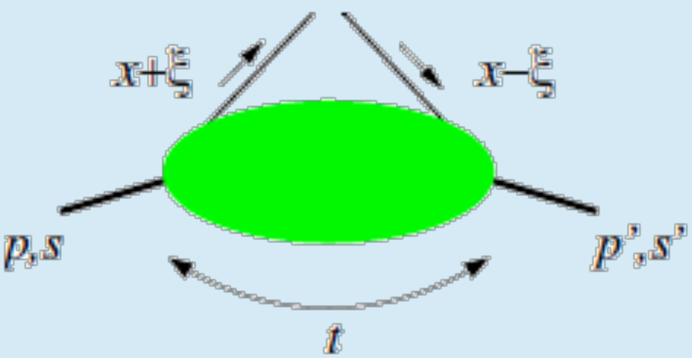


- deeply virtual Compton scattering (DVCS)



- exclusive meson production

- 4 generalized parton densities, per flavor, to describe such processes:



They depend on x, ξ, t, Q^2

- x, ξ: mom. fractions w.r.t. $P \equiv \frac{1}{2}(p+p')$

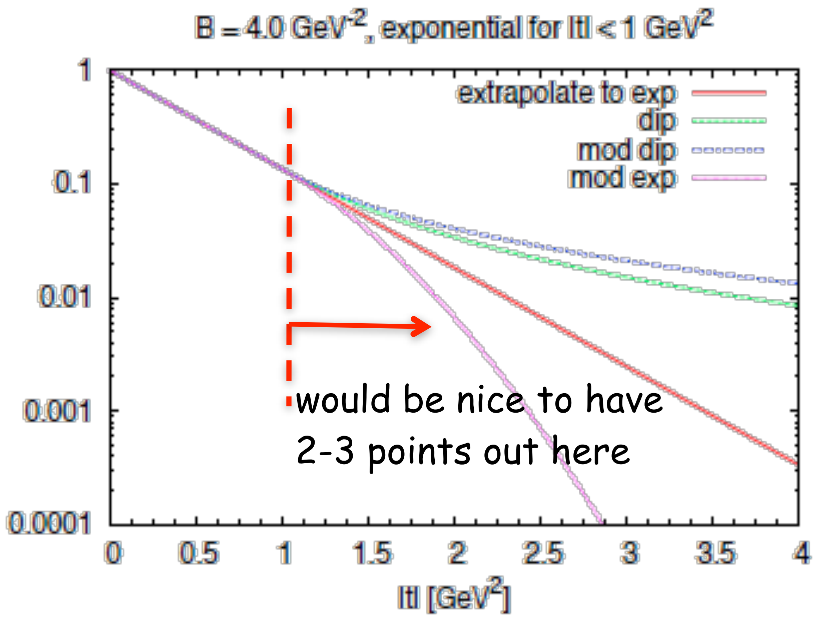
  where $\xi = (p-p')^+/(p+p')^+$

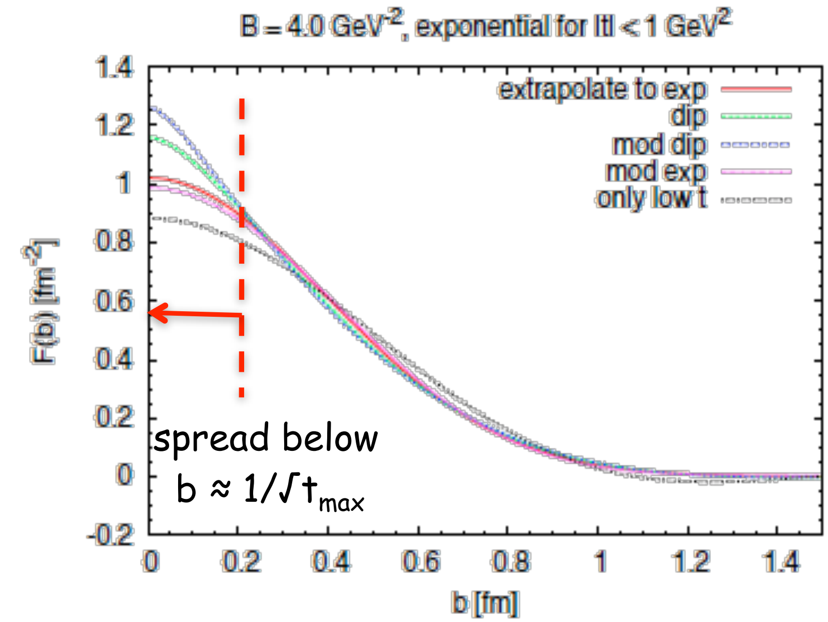
  in DVCS: x integrated and $\xi = x_B/(2-x_B)$
- t: trade for trans. momentum transfer Δ

- t-dependence relates via Fourier-transform to impact-parameter b;
- t-strongly correlated with proton angle.

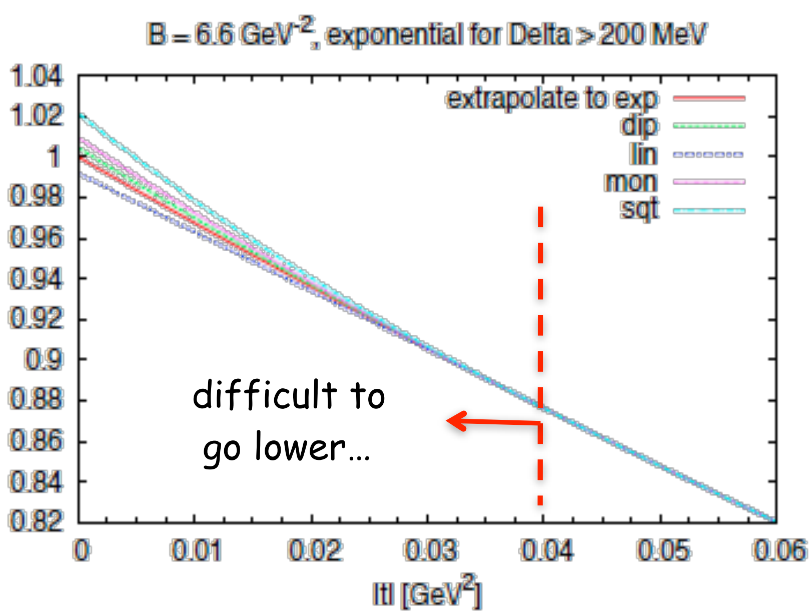
imaging through GPDs – required t-range

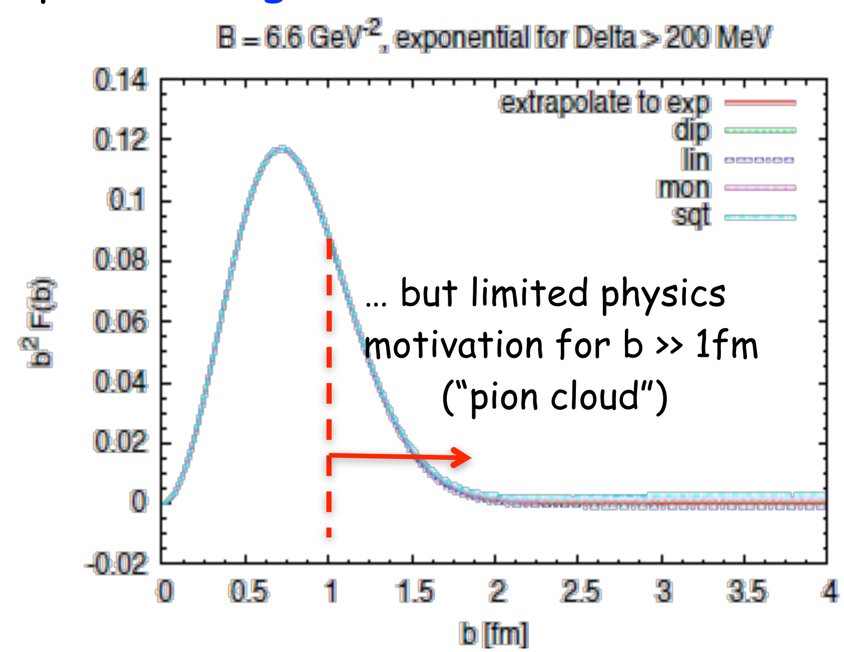
extrapolation uncertainty from **large t** and its impact on **small b**: M. Diehl

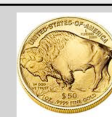




extrapolation uncertainty from **small t** and its impact on **large b**:





Science Deliverable	**Basic Measurement**	**Uniqueness Feasibility Relevance**	**Requirements**
spin structure at small x contribution of Δg, $\Delta\Sigma$ to spin sum rule	inclusive DIS	✔ 	minimal large x,Q^2 coverage about $10 fb^{-1}$
full flavor separation in large x,Q^2 range strangeness, s(x)-s(x) polarized sea	semi-inclusive DIS	✔ 	very similar to DIS excellent particle ID improved FFs (Belle,LHC,...)
electroweak probes of proton structure flavor separation electroweak parameters	inclusive DIS at high Q^2	✔  some unp. results from HERA	20x250 to 30x325 positron beam ? polarized ^3He beam ?
spatial structure down to small x through TMDs and GPDs	SIDIS azim. asym. & exclusive processes	✔  some results in valence region	p_T^H binning, t resolution, exclusivity, Roman pots, large (x,Q^2) range